

Elusive Elements of Evaporation and Runoff Behavior Hidden Within Traditional Hydrological Measurements

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Acknowledgments

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Outline of talk

- 1. Efficiency relationships**
2. The “Budyko-istic” perspective
3. Relevance to land surface model development
4. Soil moisture: Nature’s linchpin

Some definitions for this talk

Evaporation Efficiency: The fraction of the net radiative energy that is used to evaporate water from the land surface (including transpiration).

$$\frac{\lambda E}{R_{\text{net}}}$$

latent heat of vaporization

evaporation

net radiation

The diagram shows the formula for Evaporation Efficiency as a fraction. The numerator is the product of the latent heat of vaporization (λ) and evaporation (E). The denominator is the net radiation (R_net). Red arrows point from the text labels to their respective variables in the formula: 'latent heat of vaporization' points to λ, 'evaporation' points to E, and 'net radiation' points to R_net.

Runoff Efficiency: The fraction of the precipitation that is converted to streamflow.

$$\frac{Q}{P}$$

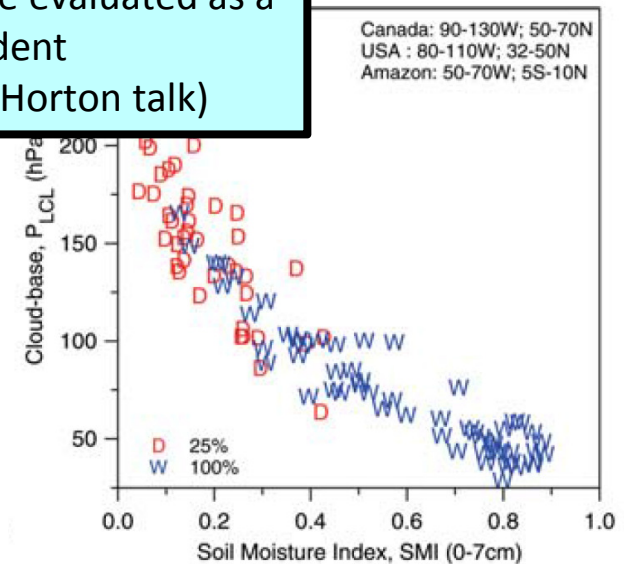
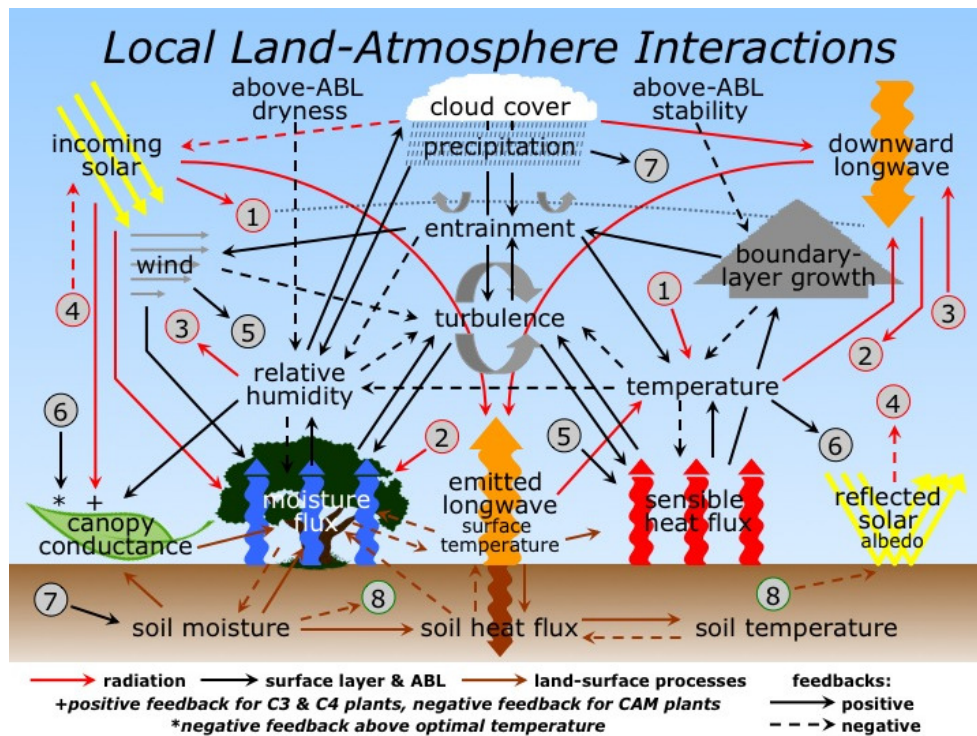
runoff

precipitation

The diagram shows the formula for Runoff Efficiency as a fraction. The numerator is runoff (Q) and the denominator is precipitation (P). Red arrows point from the text labels to their respective variables: 'runoff' points to Q and 'precipitation' points to P.

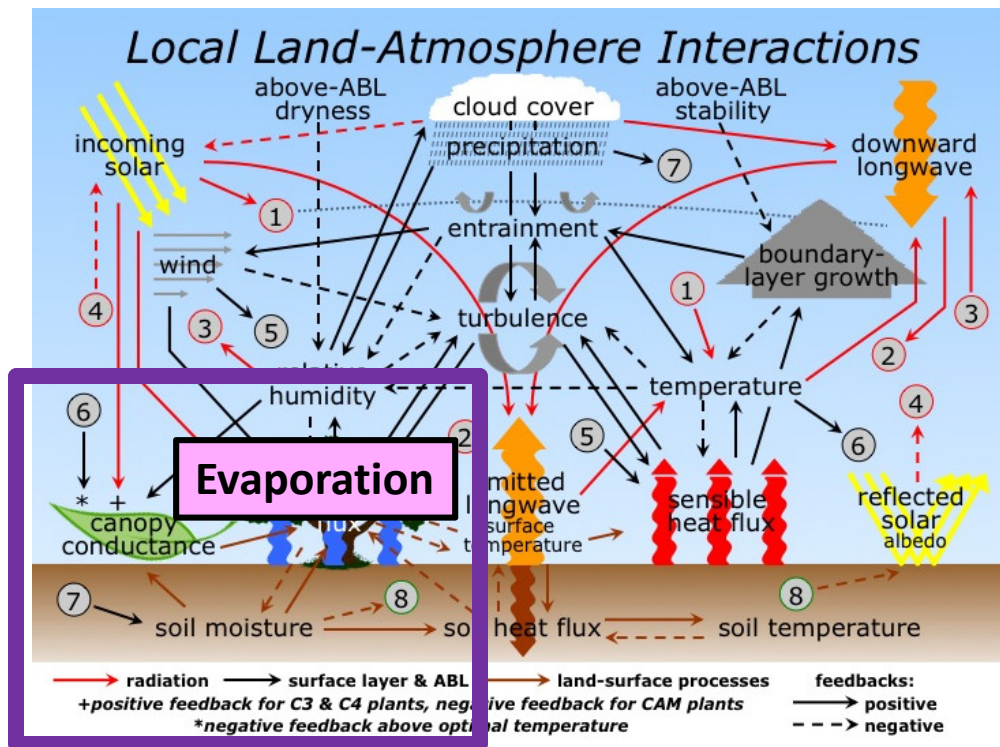
Caveat: Evaporation is controlled by complex, interacting processes spanning the land surface and boundary layer...

“...cloud and boundary layer processes and the land surface components of a model must be evaluated as a tightly coupled system, not as independent components.” (Betts, 2004 -- from his Horton talk)

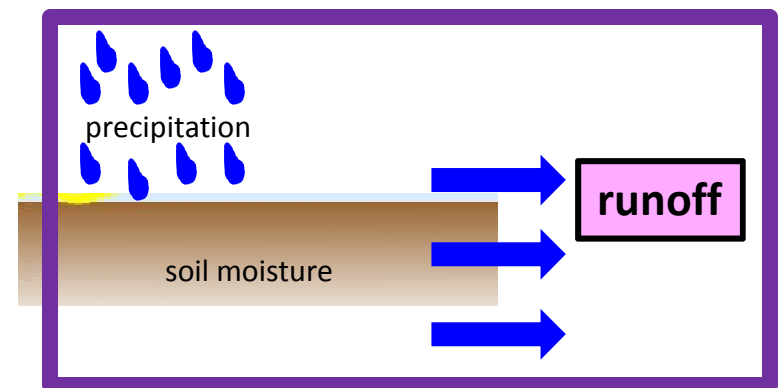


Courtesy of Mike Ek

... but in this talk we focus on the interactions between two processes (soil moisture controls on evaporation and runoff) at and below the land-atmosphere interface. In a sense, we look at a different control volume:

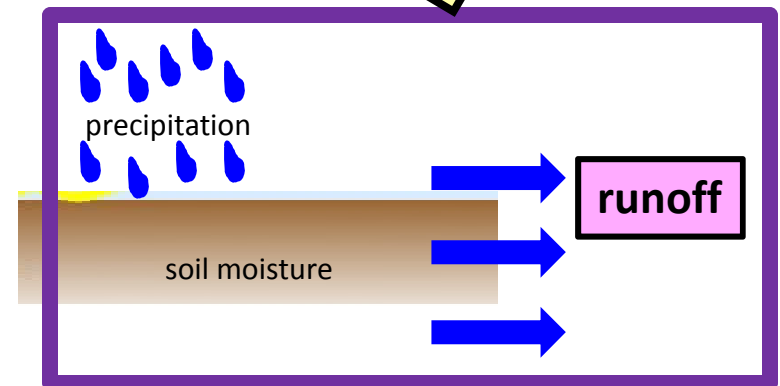
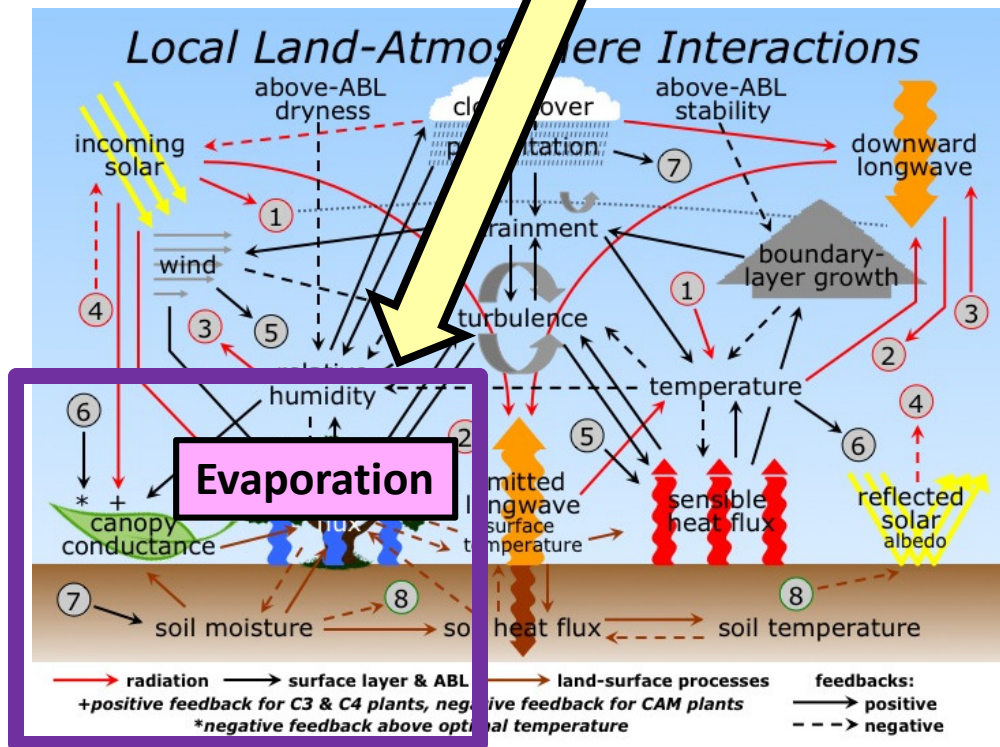


Courtesy of Mike Ek



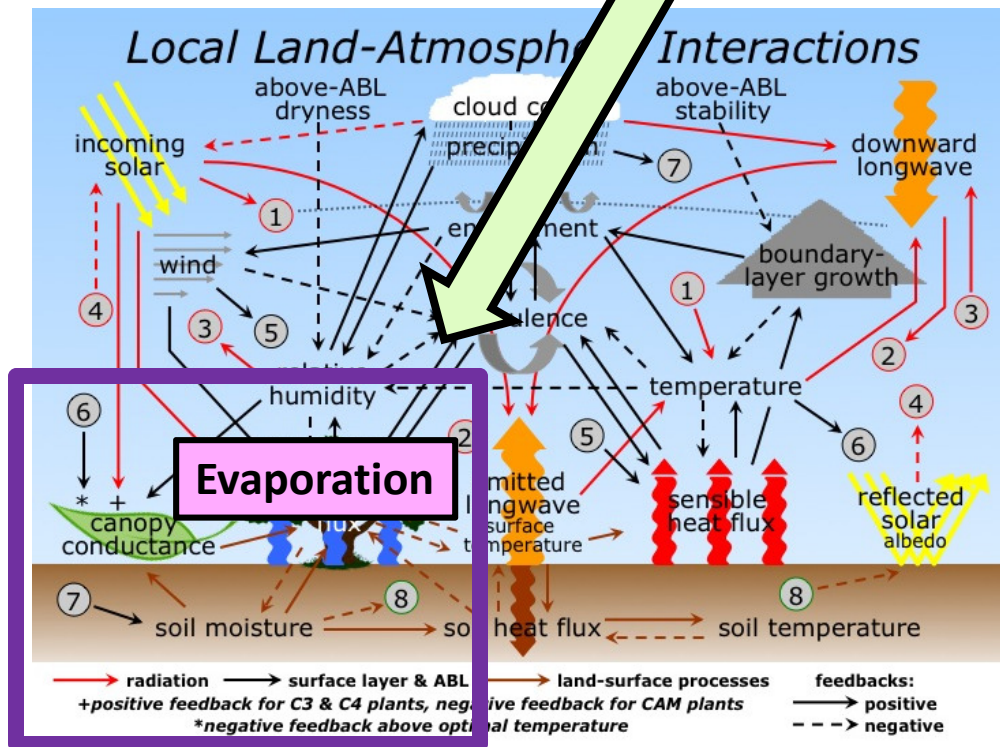
In this much simpler context, soil moisture helps to determine how much of the net radiative energy absorbed by the land surface is used to evaporate water: $\lambda E/R_{\text{net}} = f_1(W)$

... and how much of the precipitation runs off into streams: $Q/P = f_2(W)$

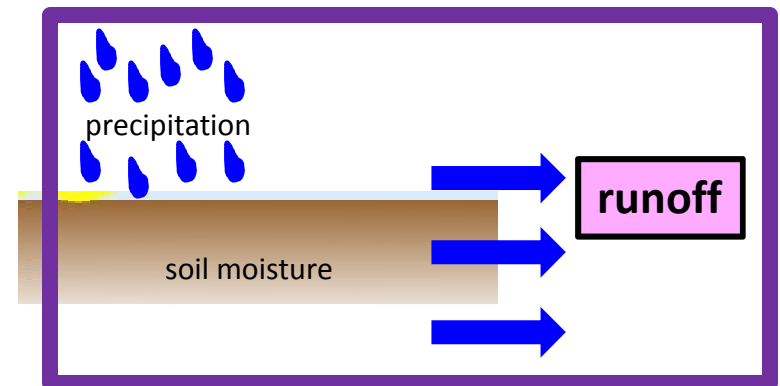


Courtesy of Mike Ek

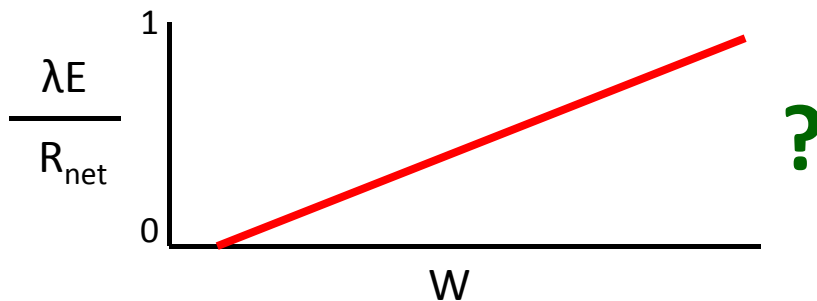
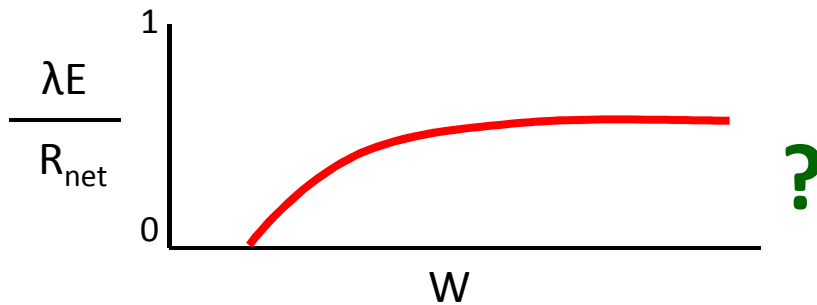
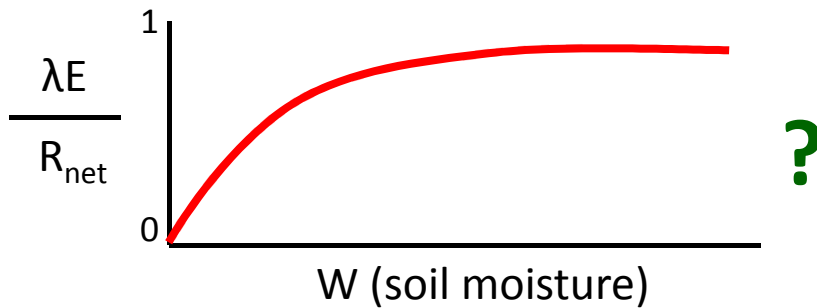
Each process affects the other! But what is their joint impact?



Courtesy of Mike Ek

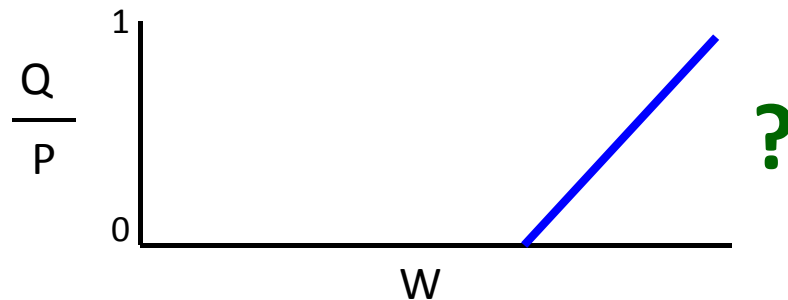
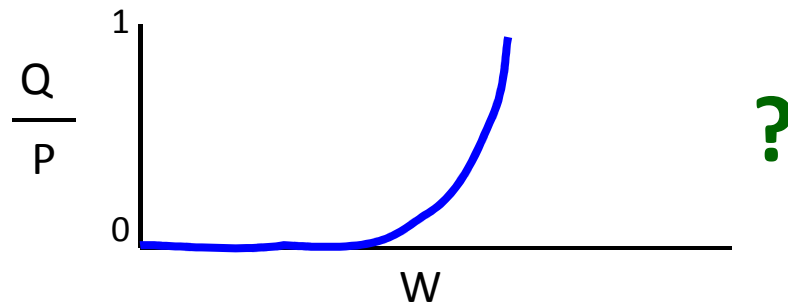
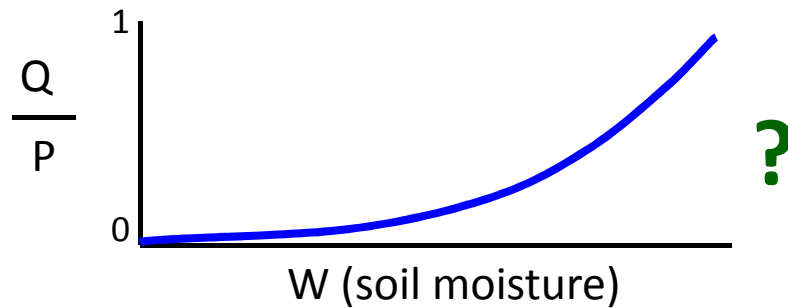


Make assumption: evaporation efficiency either increases with soil moisture or is independent of soil moisture.



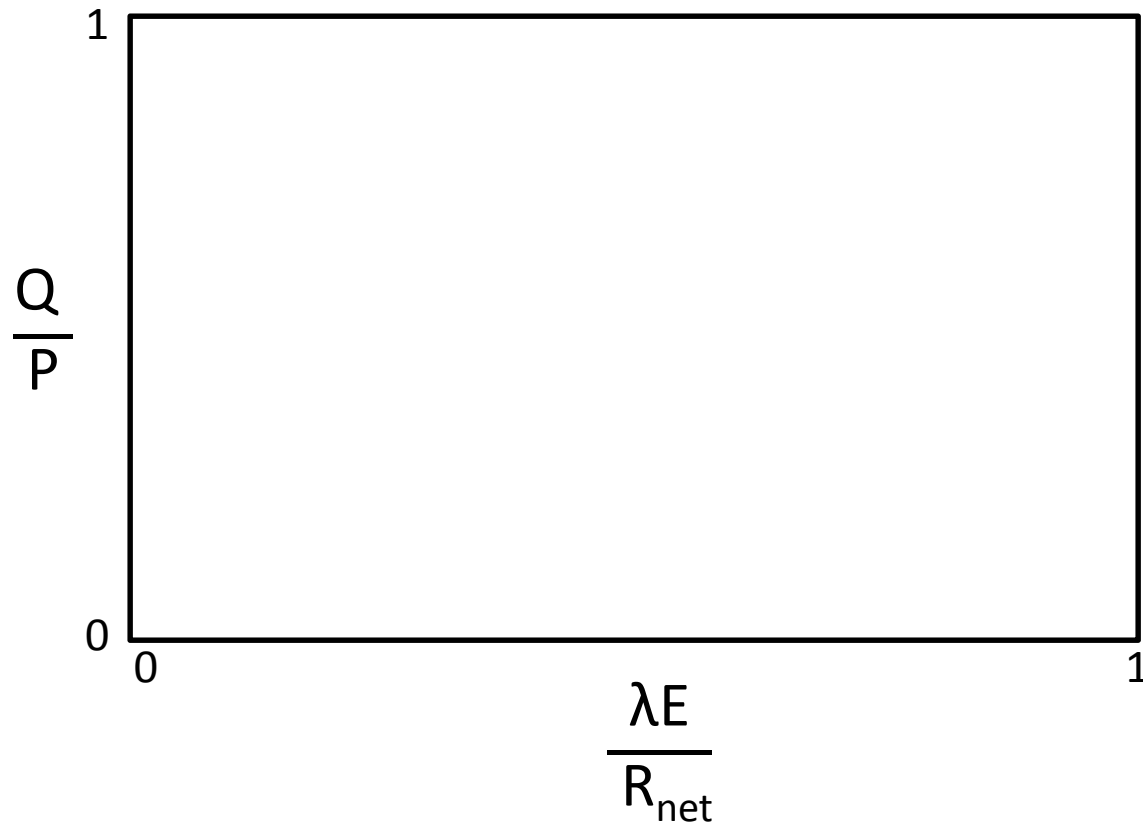
Don't worry right now about what the relationship looks like—just assume that it exists...

Make a similar assumption regarding runoff efficiency – it too will either increase with soil moisture or be independent of soil moisture.

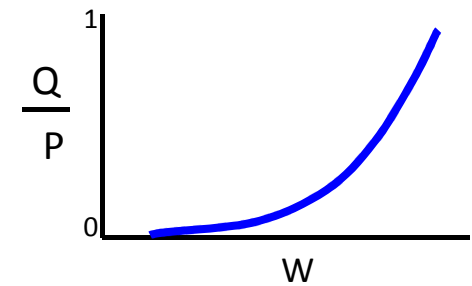
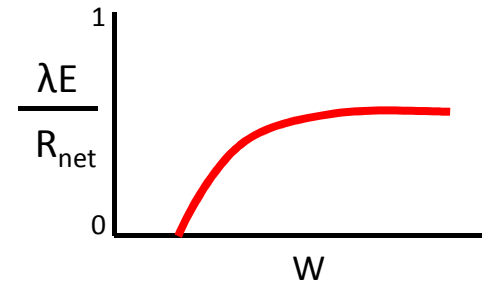
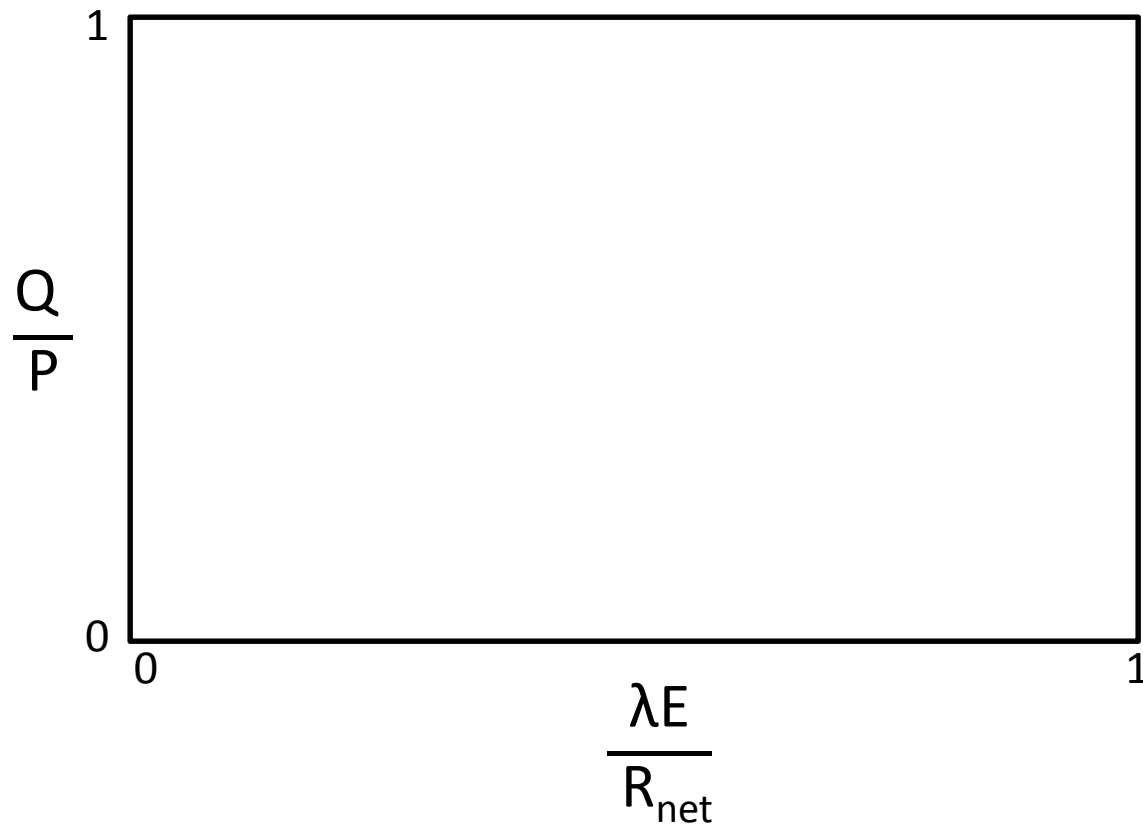


Again, for now,
just assume that
some relationship
exists.

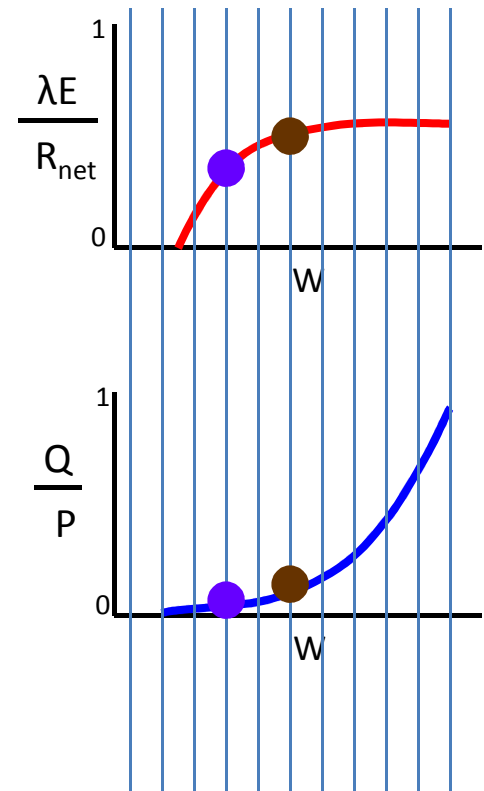
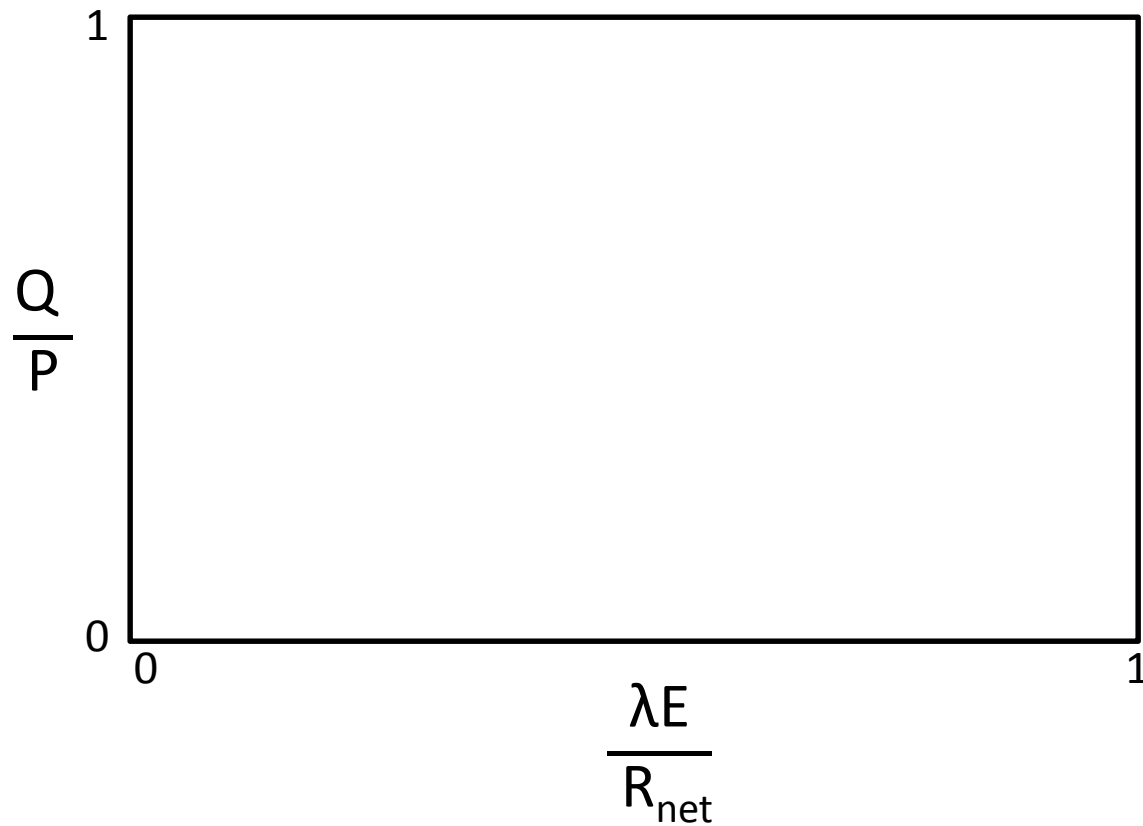
Under these assumptions, there is some relationship between evaporation efficiency and runoff efficiency.



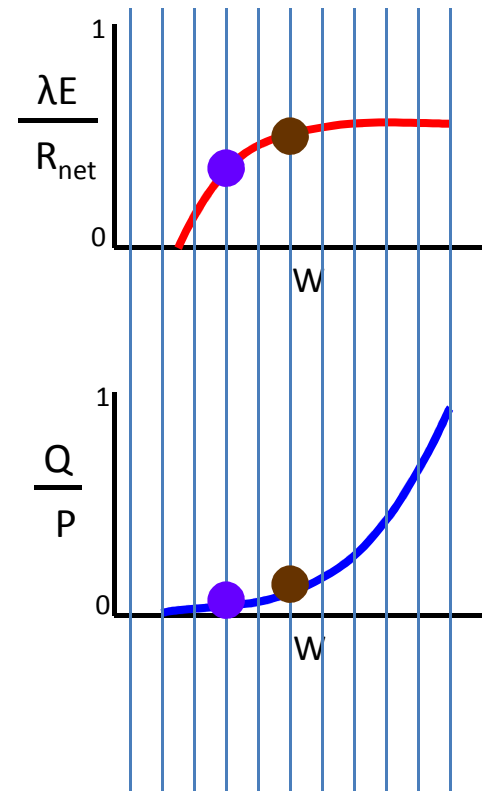
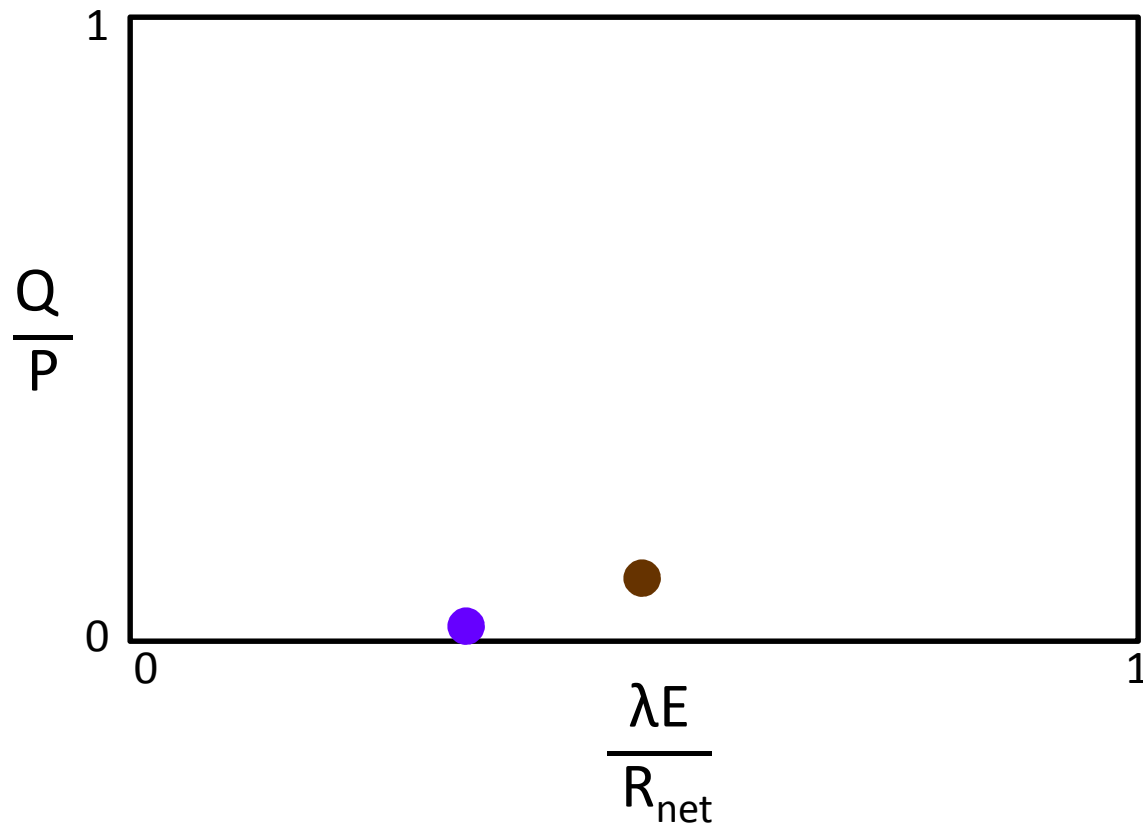
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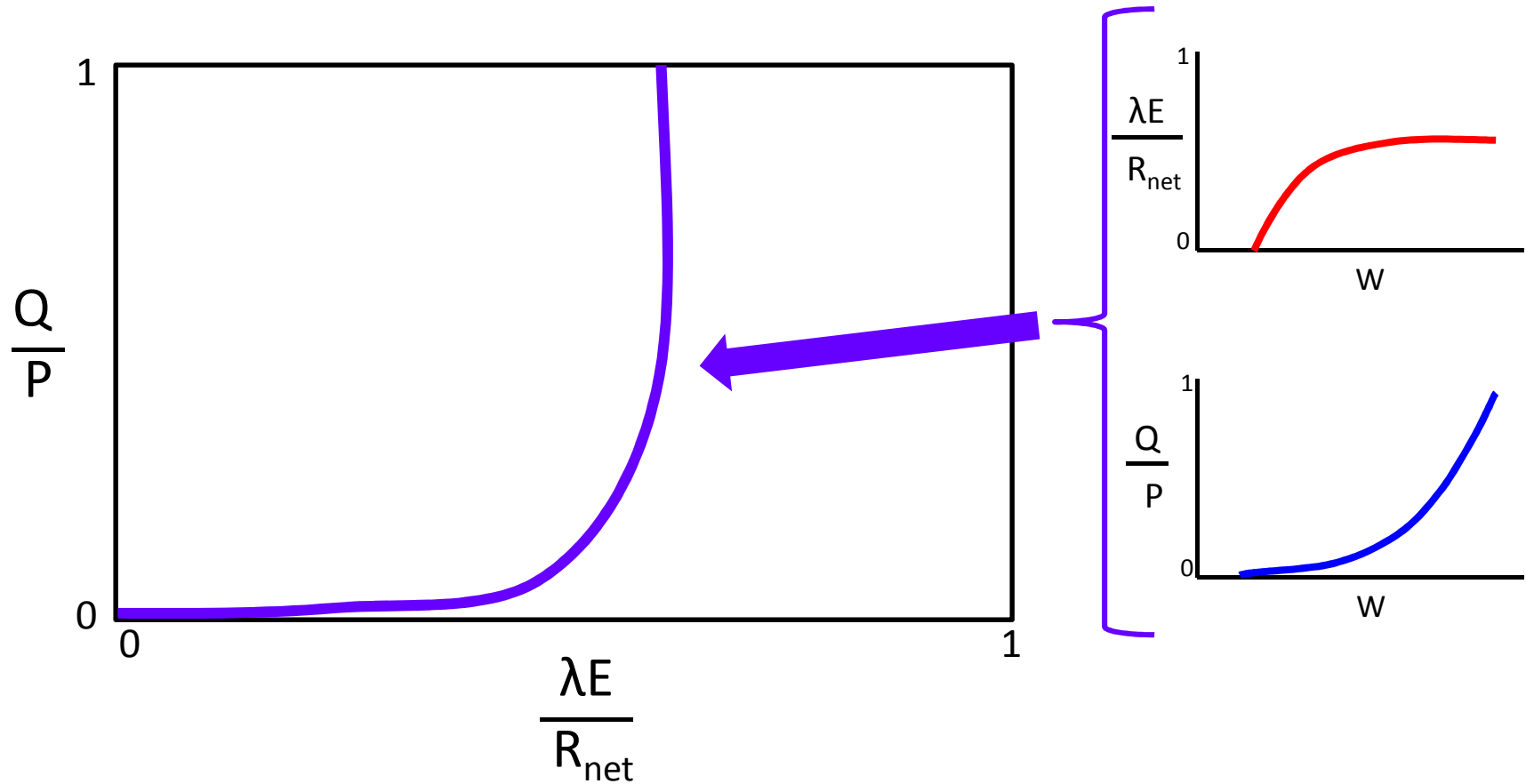
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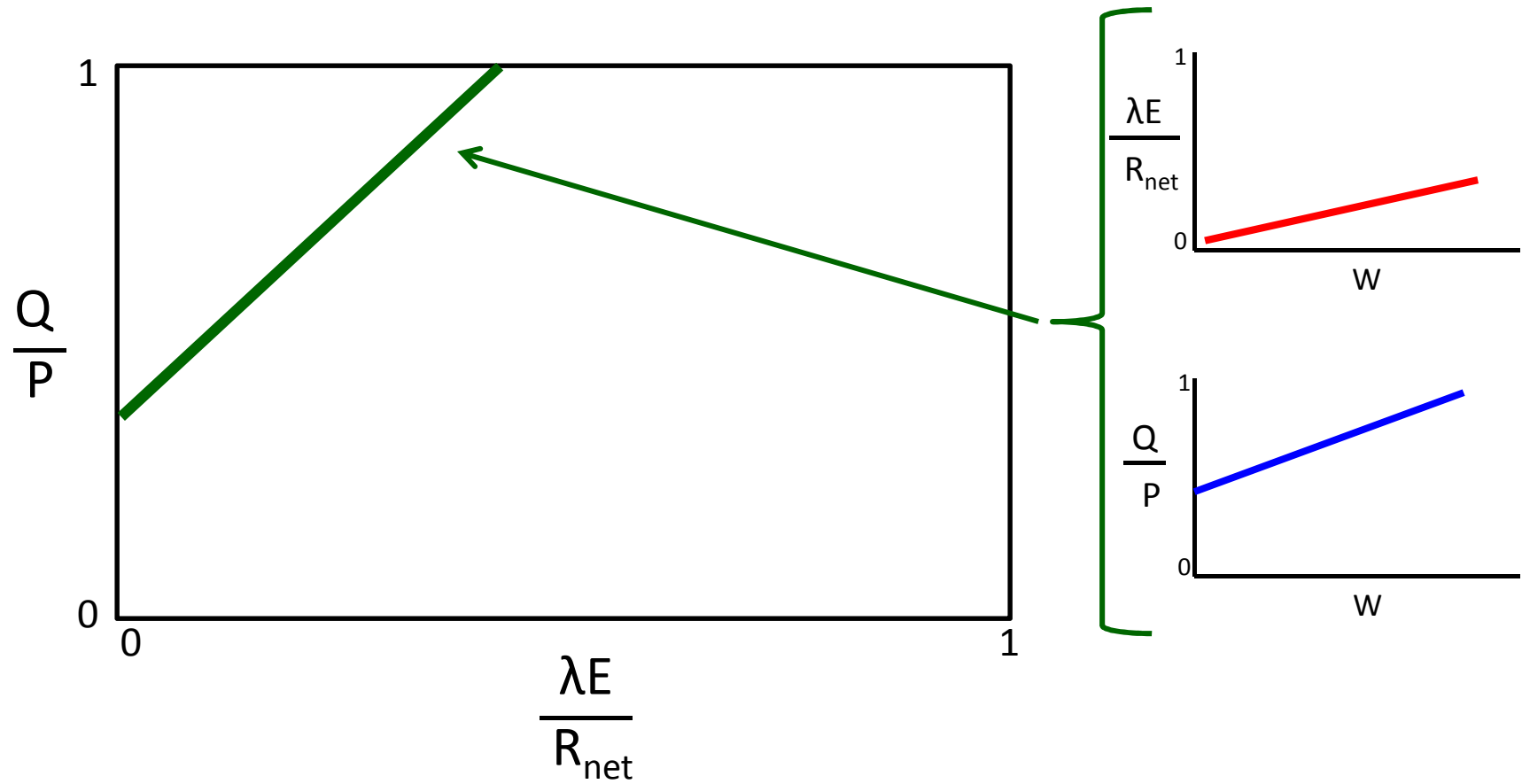
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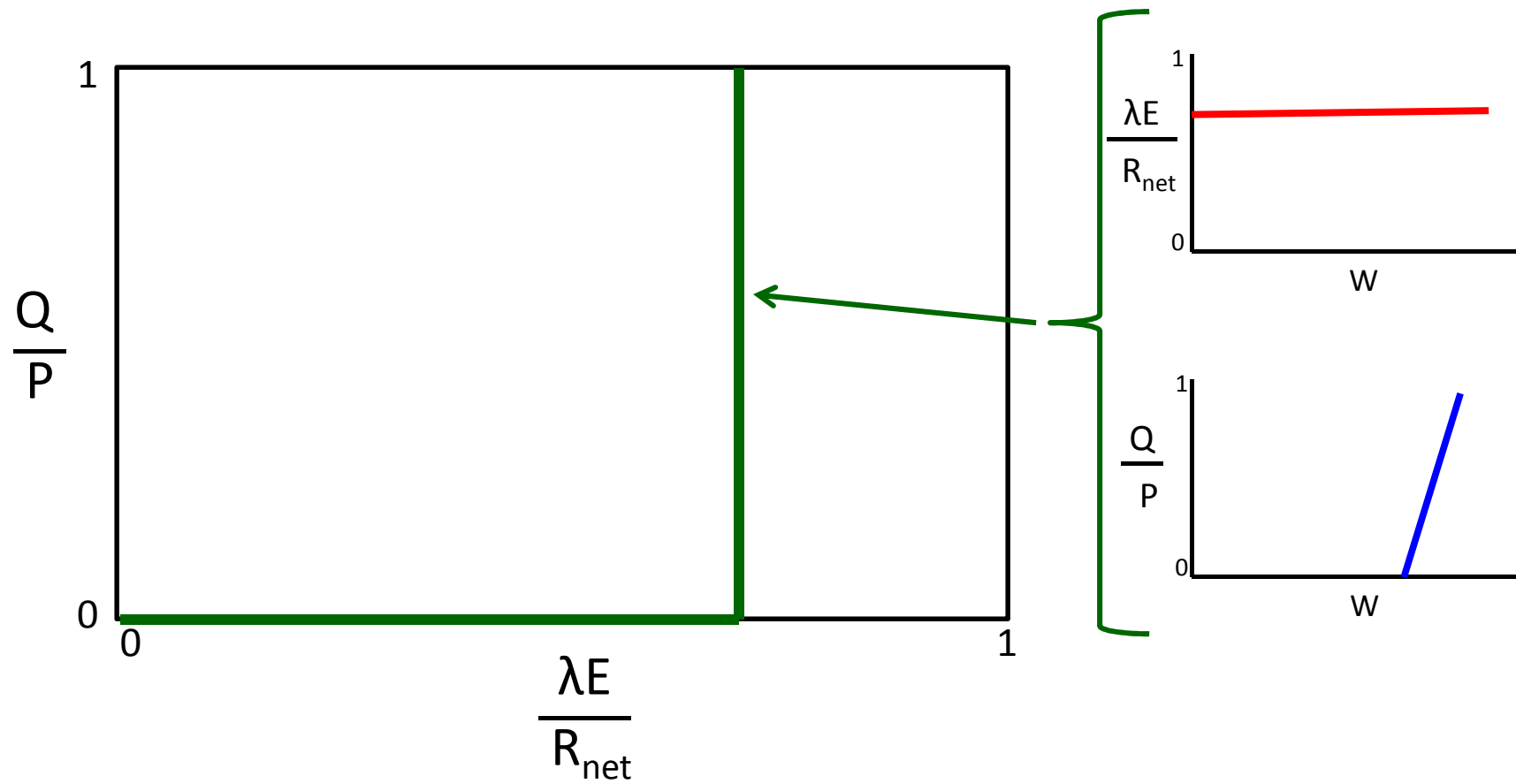
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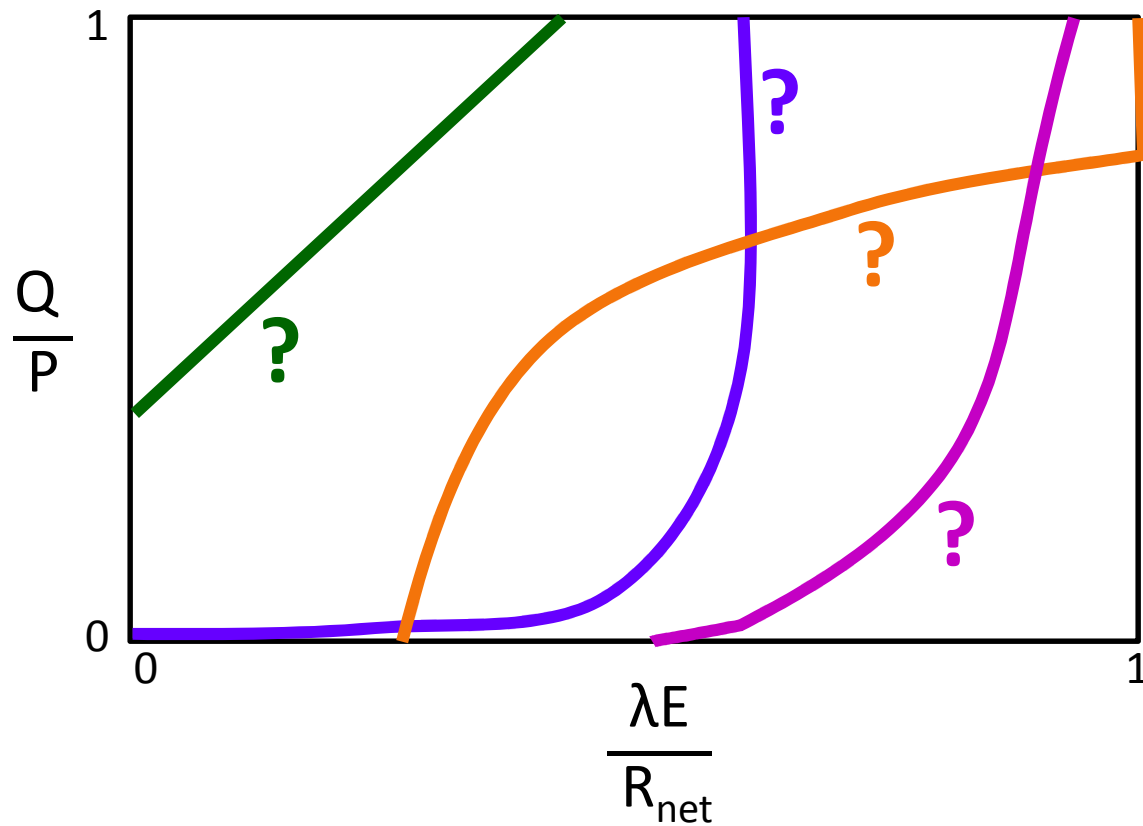
Another example...



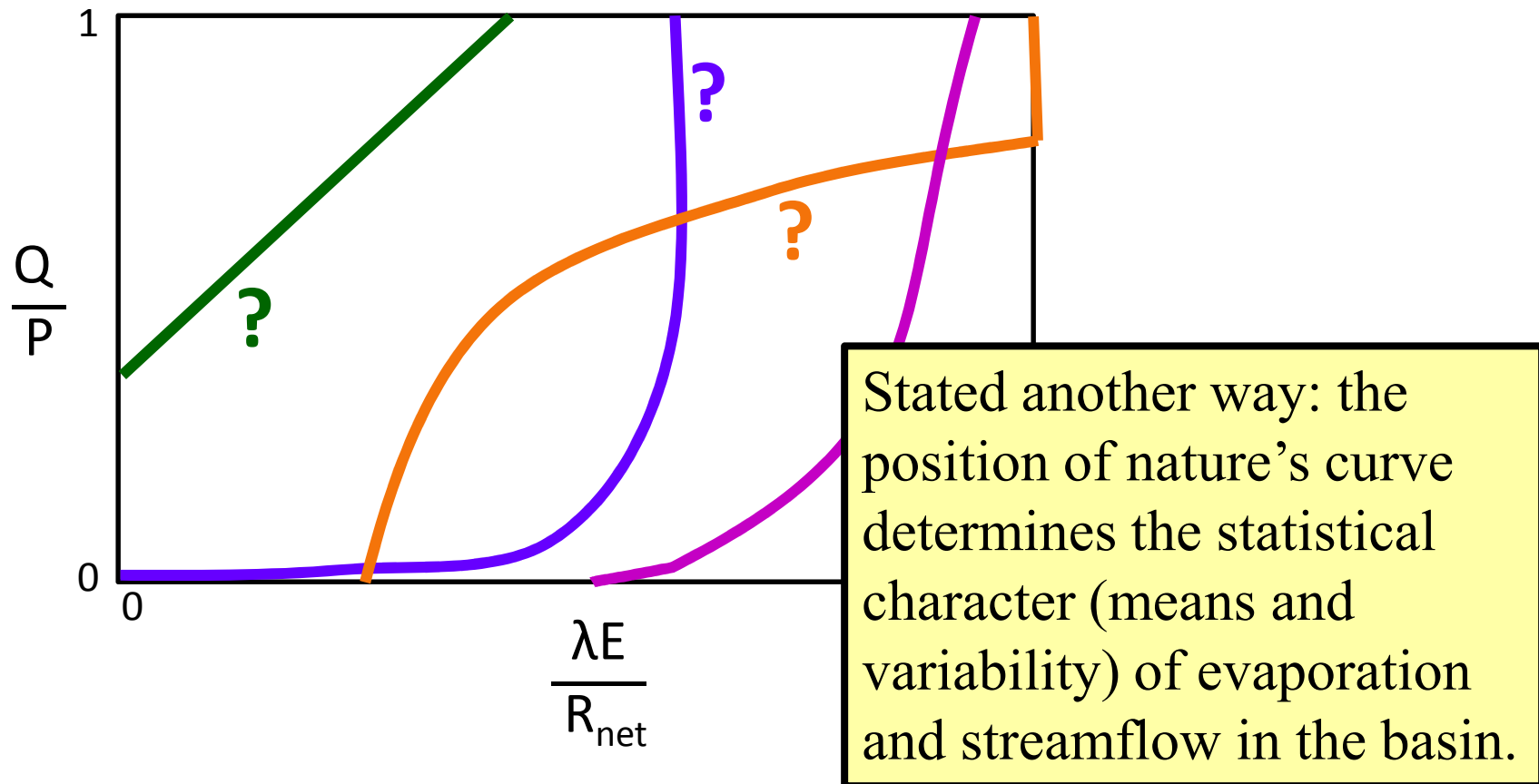
And another example...



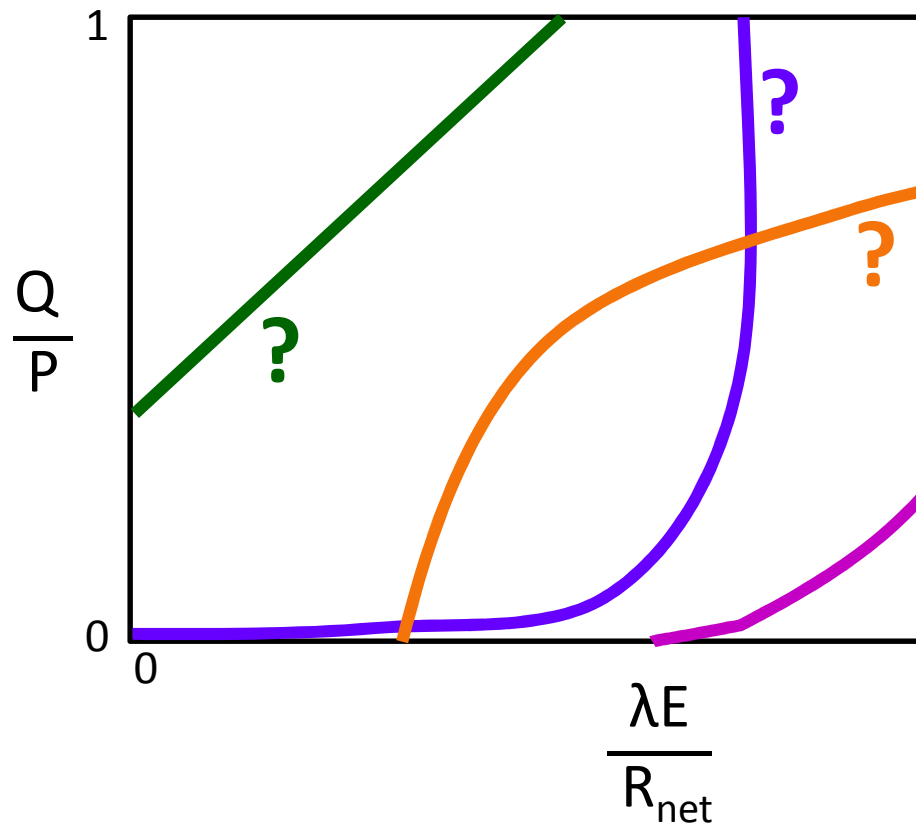
Hypothesize: there is some curve in “efficiency space” that represents, *to first order*, how nature behaves in a given basin.



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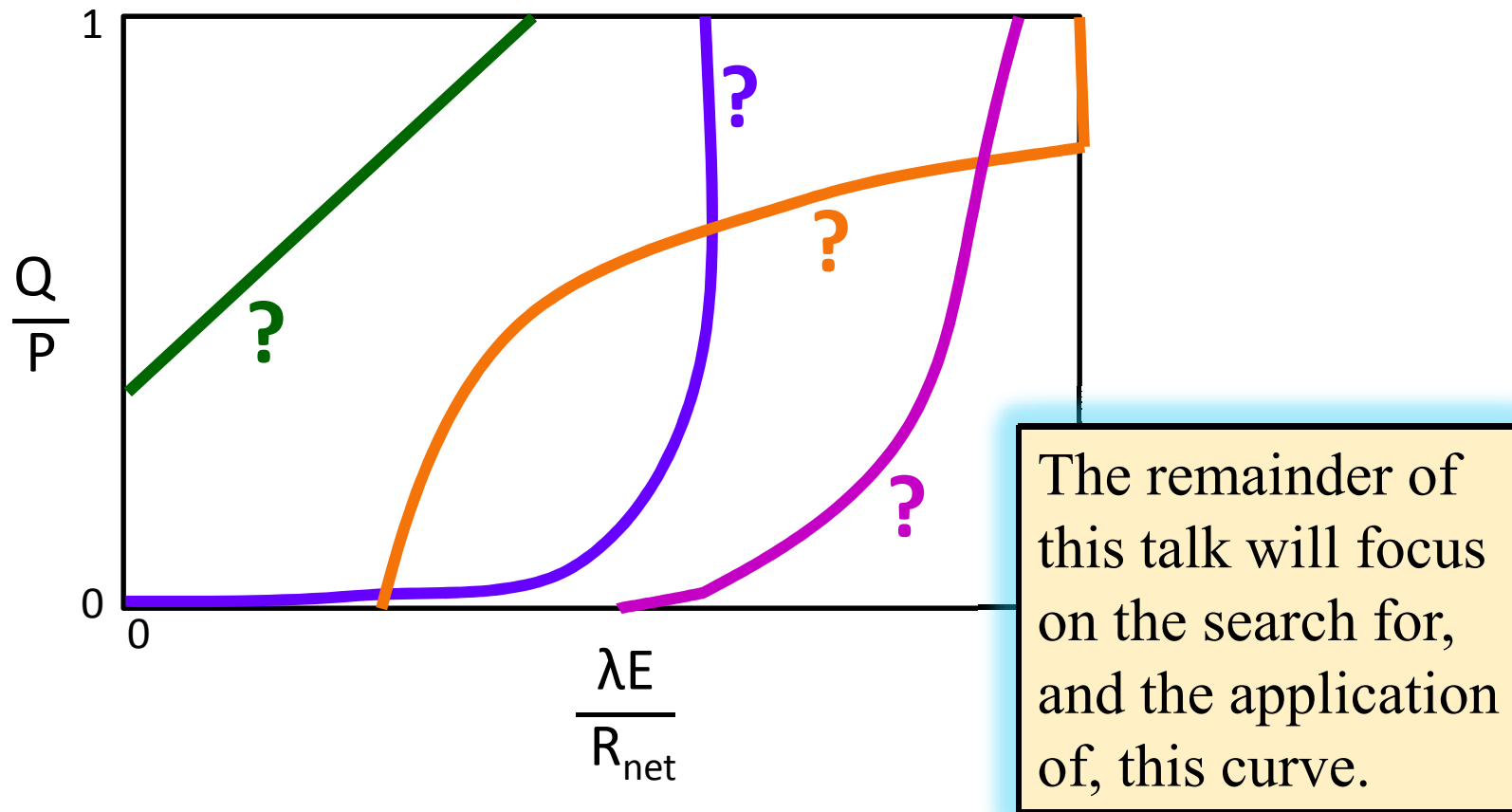


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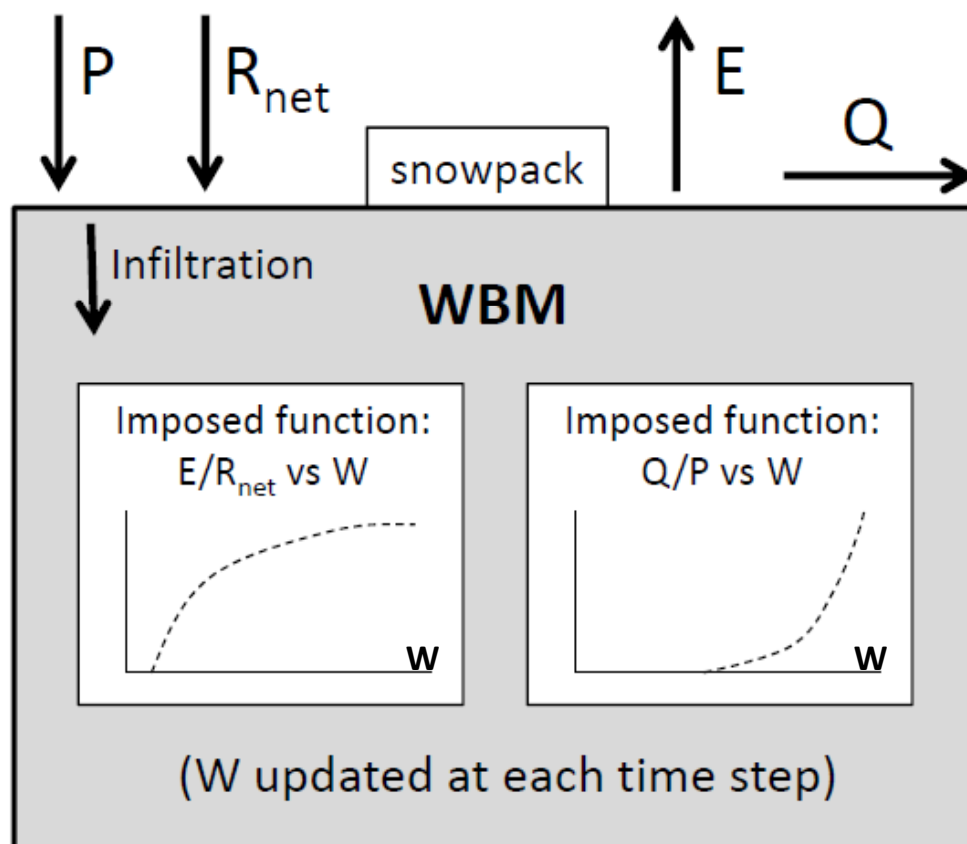
Such considerations emphasize the critical idea that it is the **joint operation** of evaporation and runoff processes that determine hydrological behavior – in model development, it is dangerous to focus inordinately on one process (e.g., Koster and Milly '97).

Hypothesize: there is some curve in “efficiency space” that represents, *to first order*, how nature behaves in a given basin.



Exploration tool: Simple water balance model (WBM)

From observations



Time step: daily

Integration time: ~ 50 yr

Domain: Continental U.S.

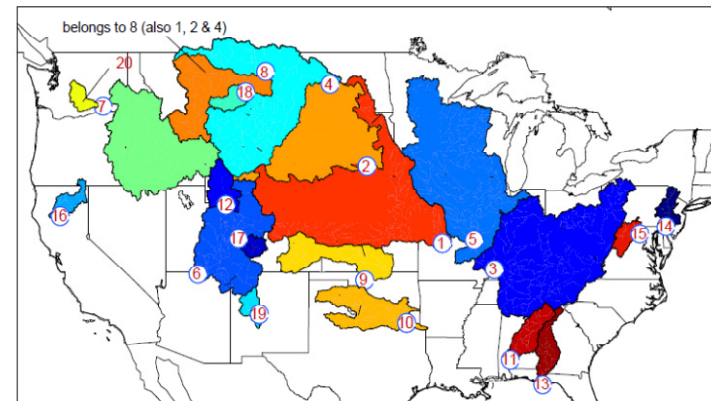
Reference: Koster and Mahanama, J. Hydromet., 13, 1604-1620, 2012

Yes, this tool is *simple*:

- The same functions are used everywhere within region studied (e.g., ignoring spatial variability in vegetation and topography) and at all times (e.g., ignoring seasonality in vegetation).
- It lacks treatments of (for example) baseflow and interception loss.
- It lacks a treatment of the surface energy balance.
- And so on... And so on...

Even so, we have found (Koster and Mahanama 2012) that it successfully captures, to first order, the important controls on hydroclimatic variability operating in a complex land surface model and (presumably) in nature.

Validation data: naturalized streamflow measurements in large-scale basins across the U.S.



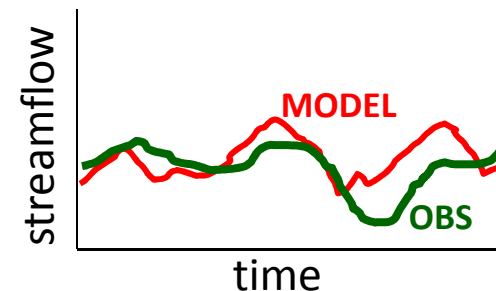
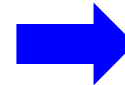
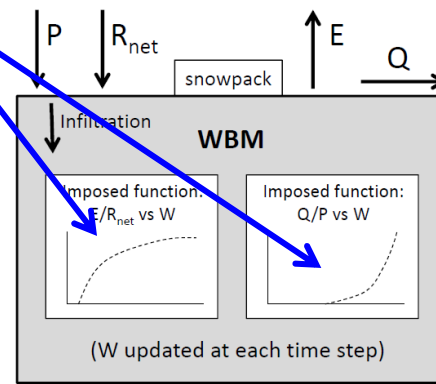
Analysis approach:

1. Select:

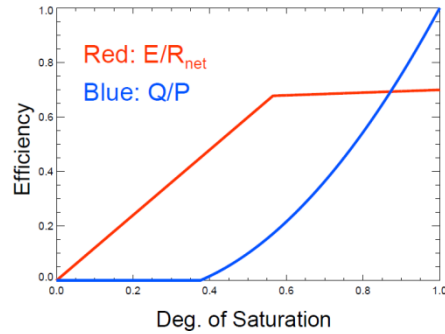
- ☐ $\lambda E/R_{\text{net}}$ -vs-W curve
- ☐ Q/P-vs-W curve
- ☐ Water holding capacity

2. Drive the WBM across CONUS with obs-based forcing \Rightarrow produce simulated streamflows in basins

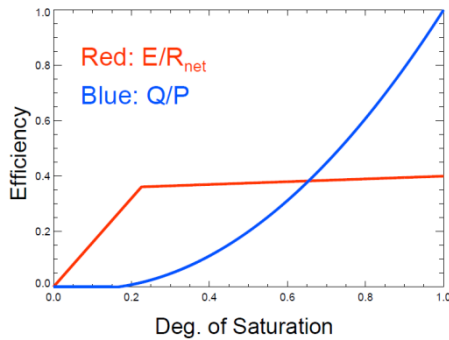
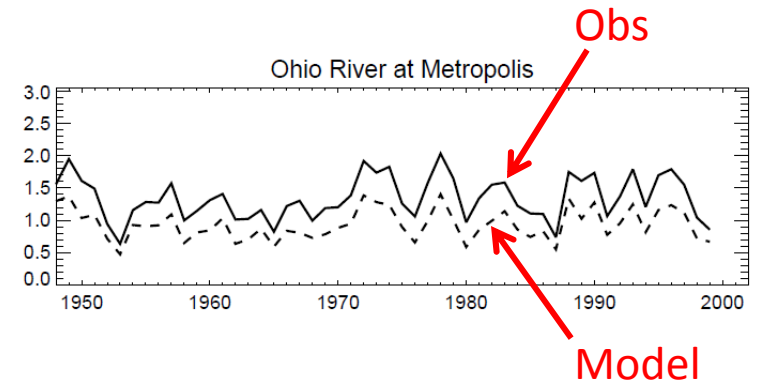
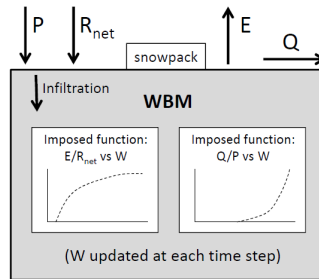
3. Evaluate streamflow against observations, in terms of RMSE.



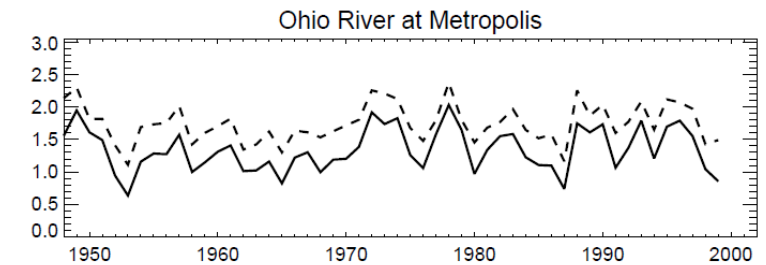
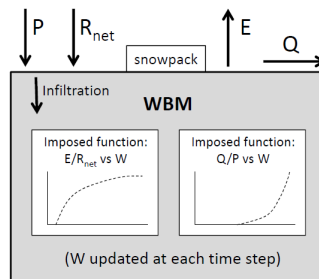
Examples



Forcing Data



Forcing Data

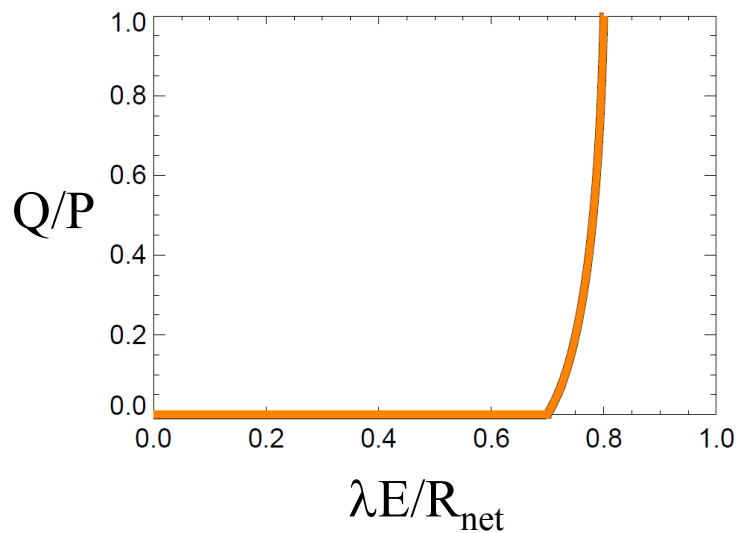
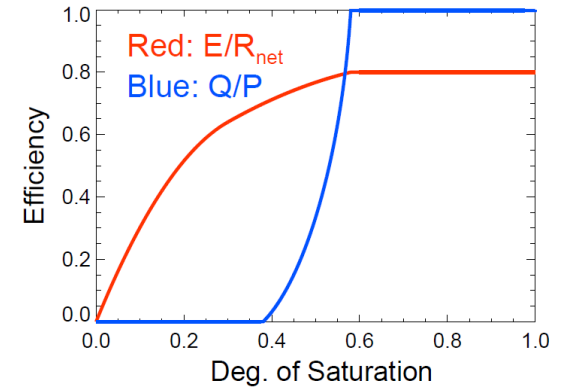
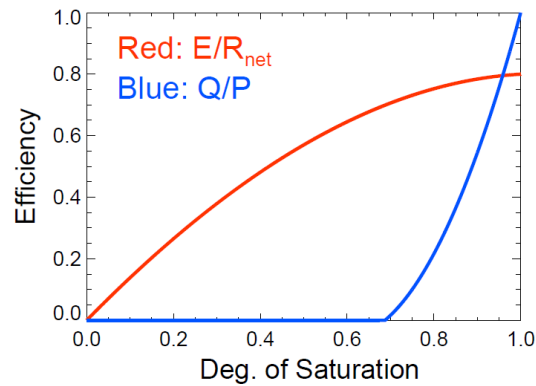
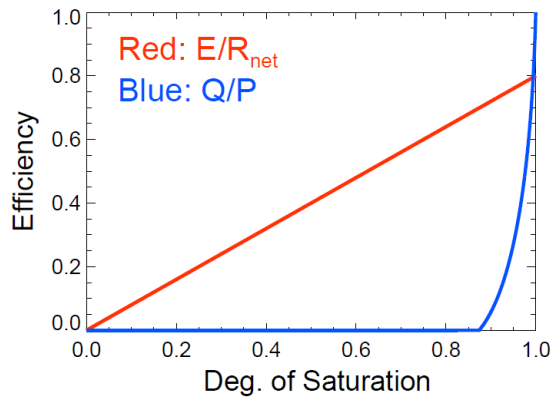


(Water holding capacity used here corresponds to a depth of 0.75 m)

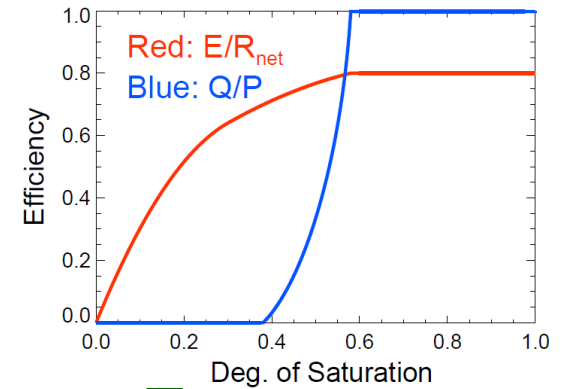
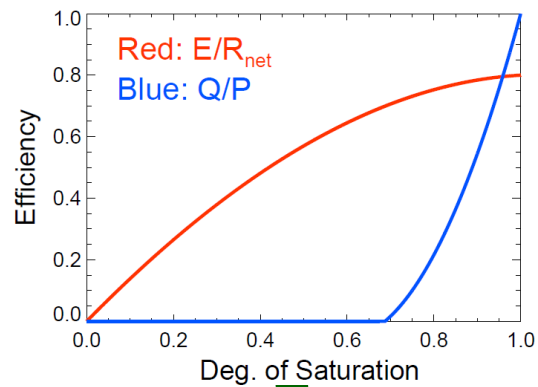
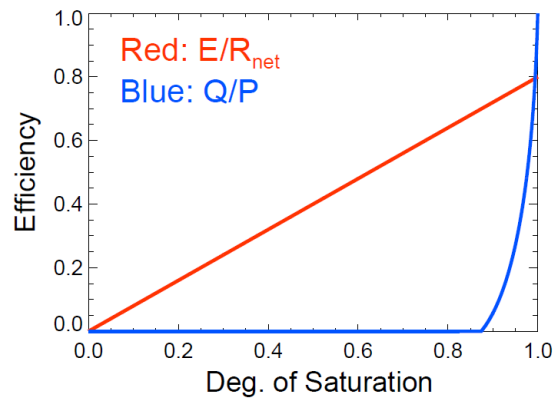
A finding that greatly simplifies this analysis, and indeed allows us to use the WBM to examine this talk's main hypothesis:

Pairs of $\lambda E/R_{net}$ -vs- W and Q/P -vs- W curves with the same $\lambda E/R_{net}$ -vs- Q/P relationship produce very similar results!

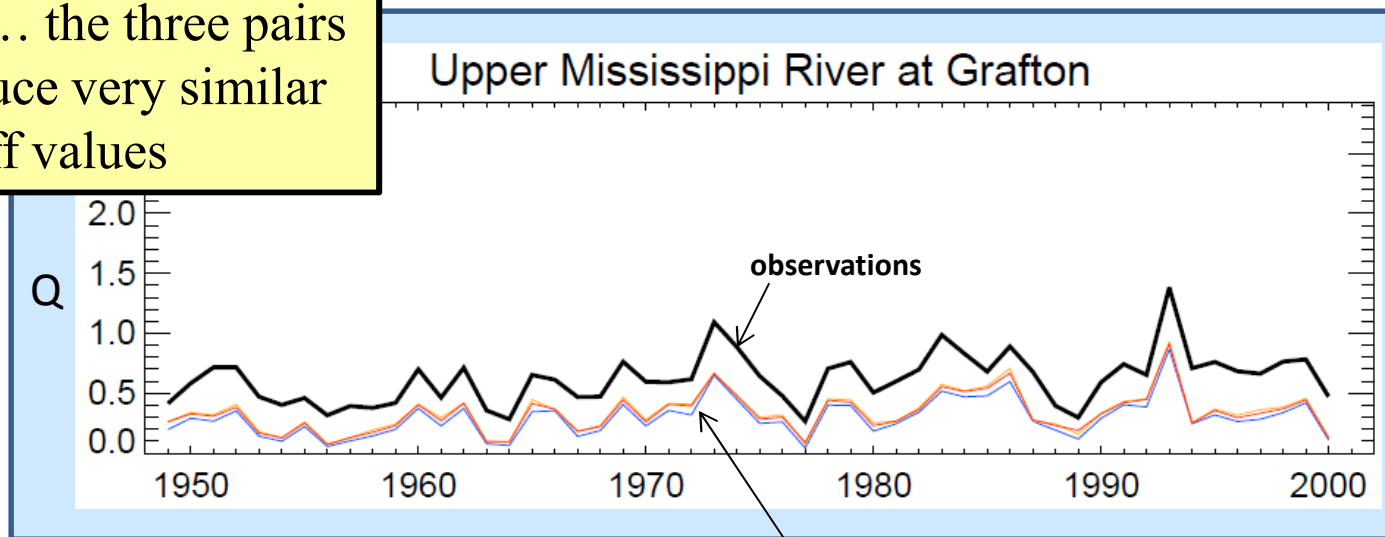
Example:



All pairs of efficiency functions collapse onto the same curve in efficiency space.

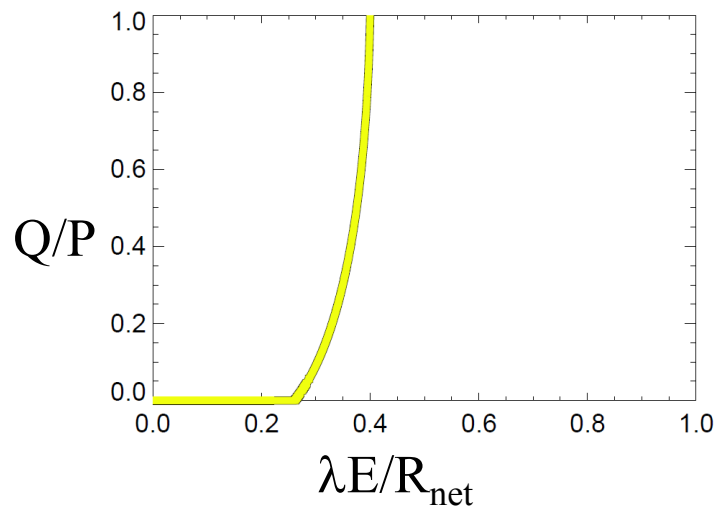
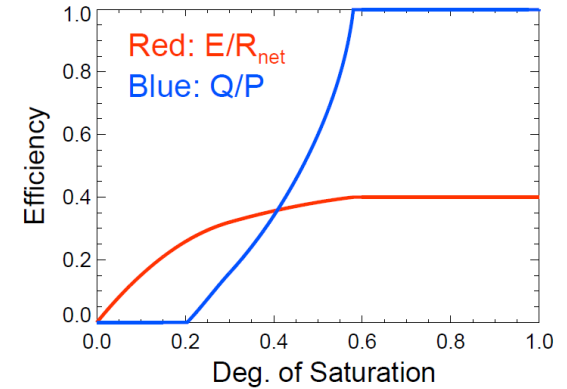
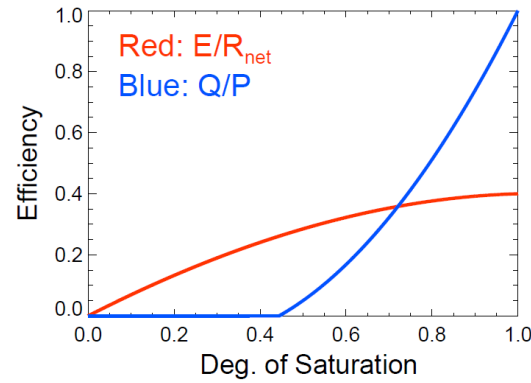
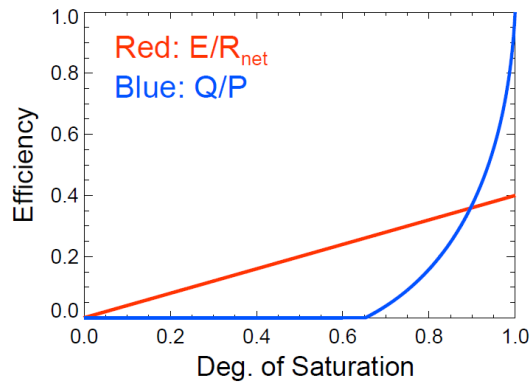


And... the three pairs produce very similar runoff values

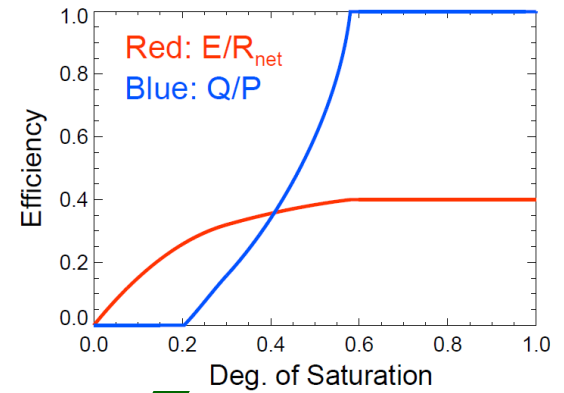
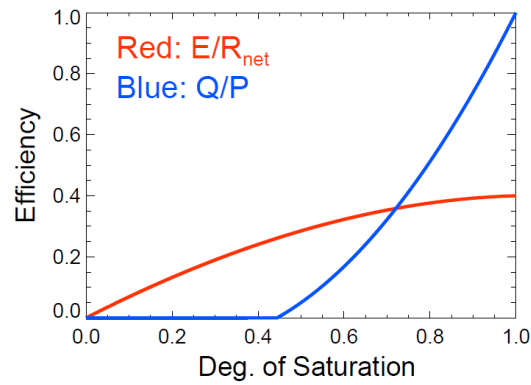
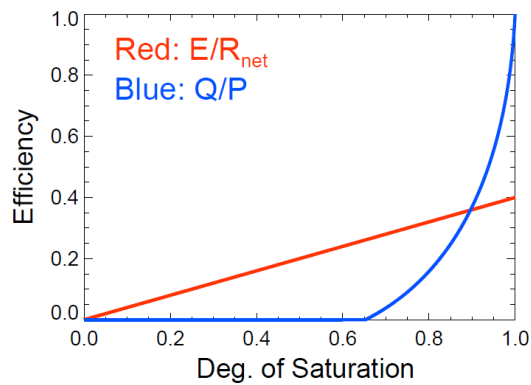


3 sets of WBM results

Another example:

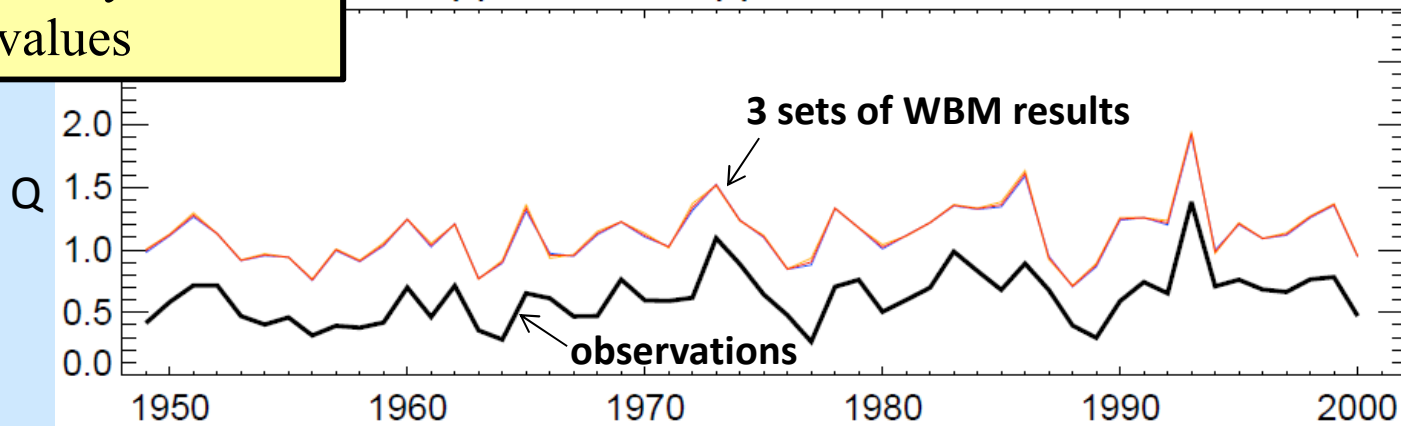


All pairs of efficiency functions collapse onto the same curve.

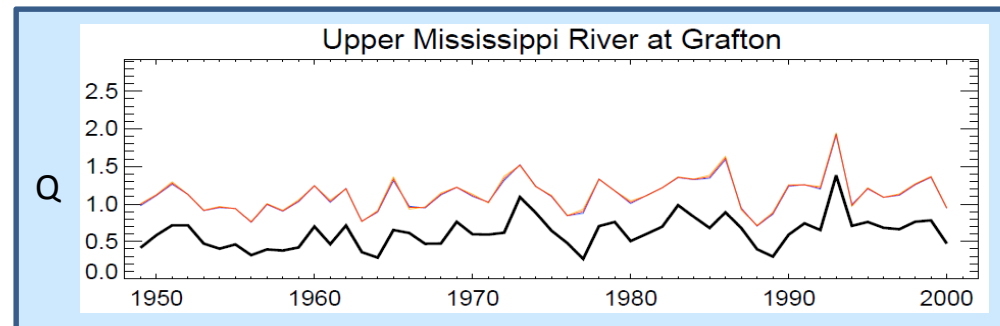
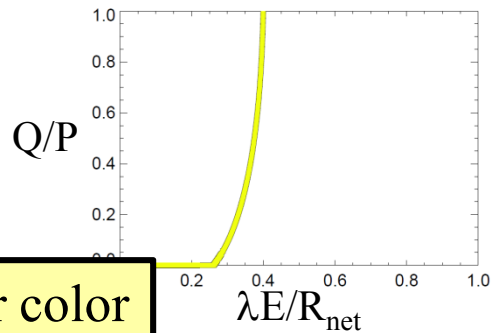
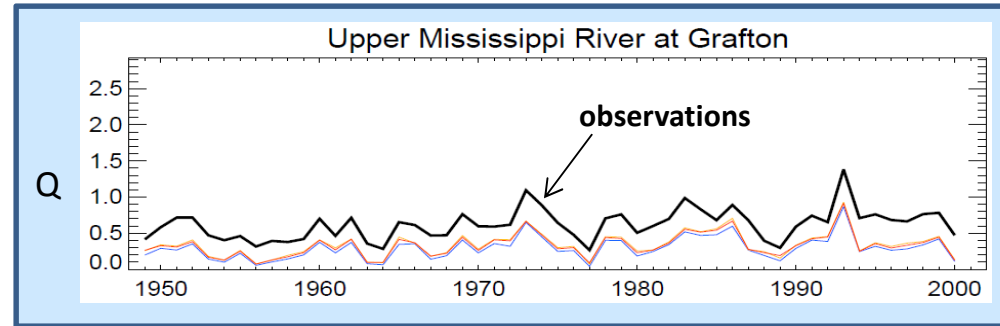
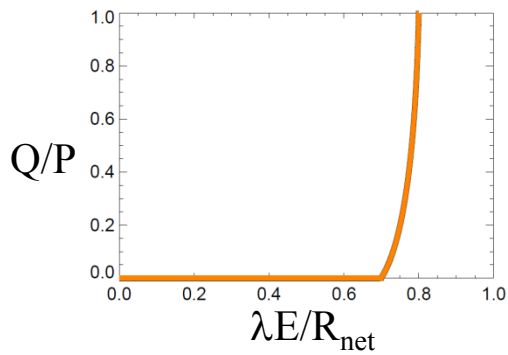


Again, the three pairs produce very similar runoff values

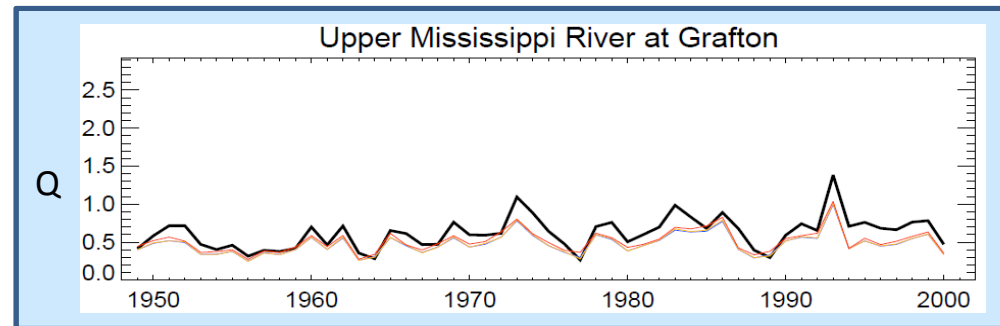
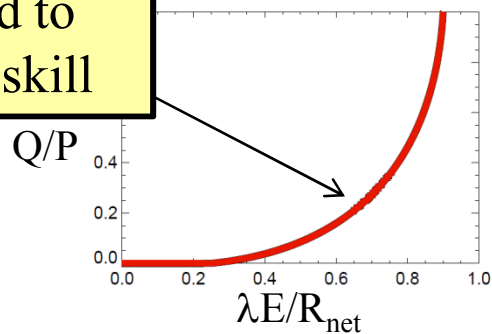
Upper Mississippi River at Grafton



Summary of examples:

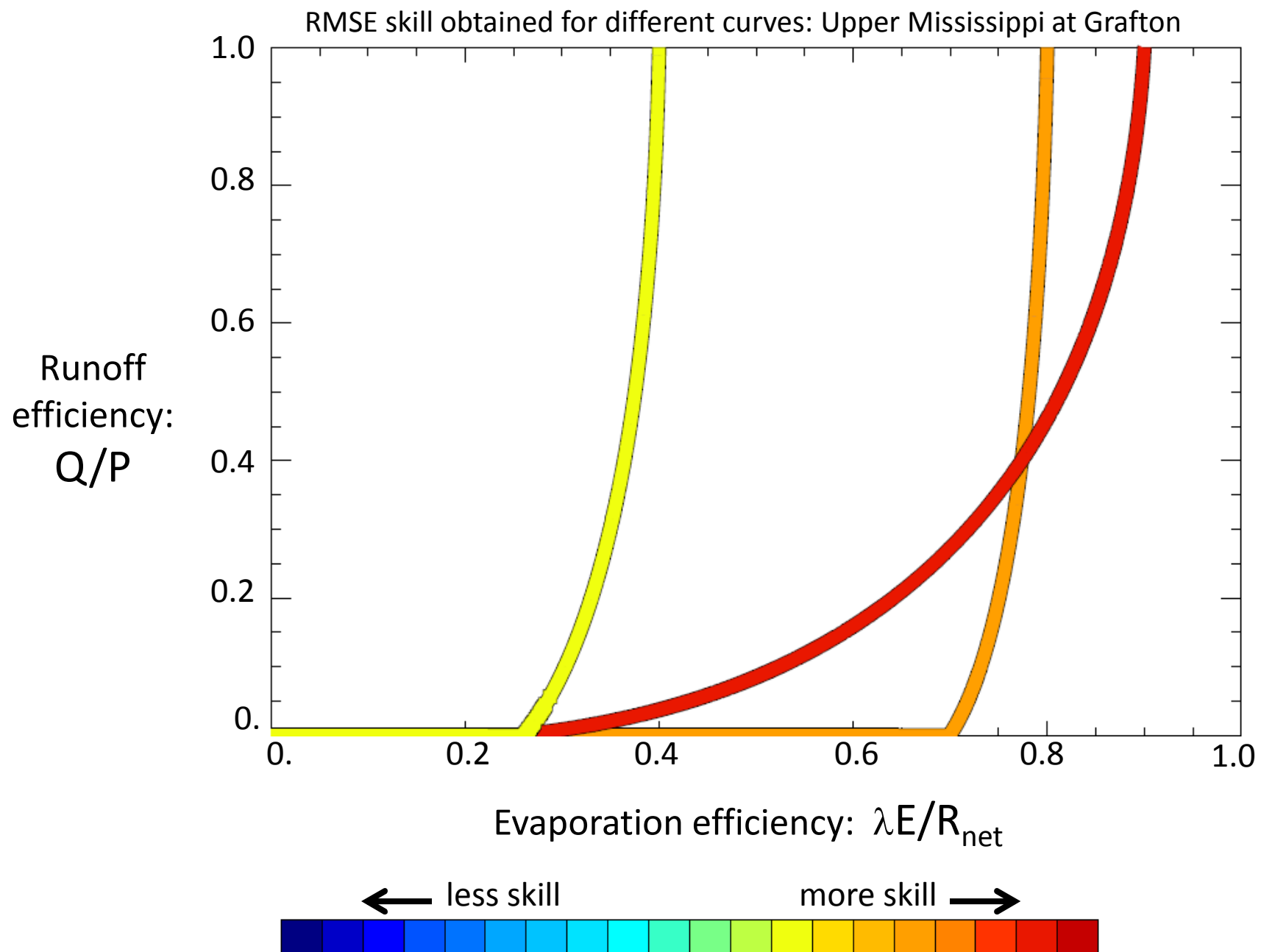


Redder color
indexed to
higher skill

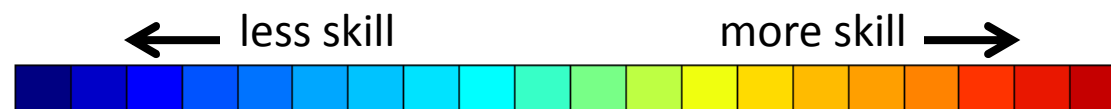
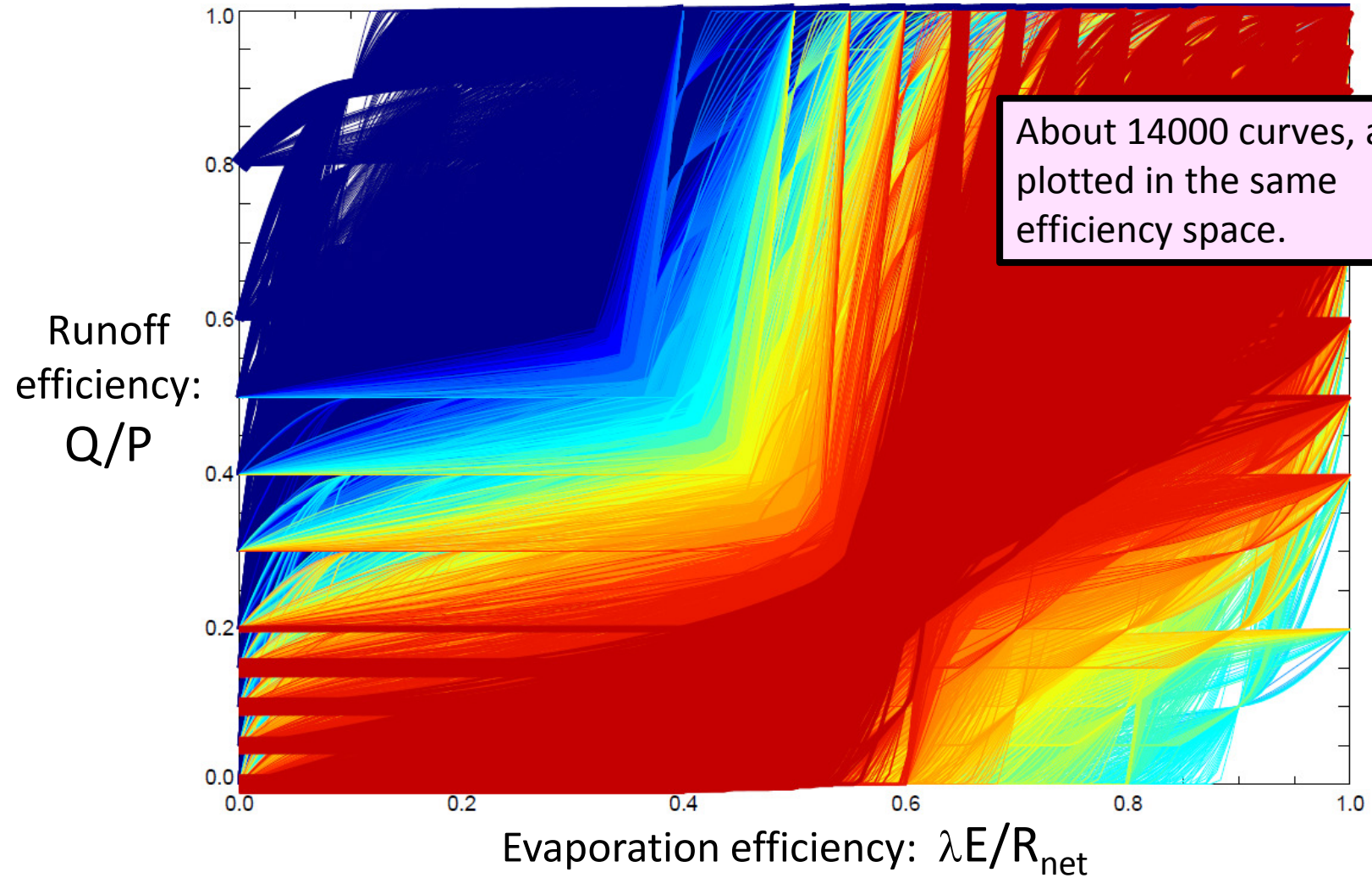


← less skill more skill →

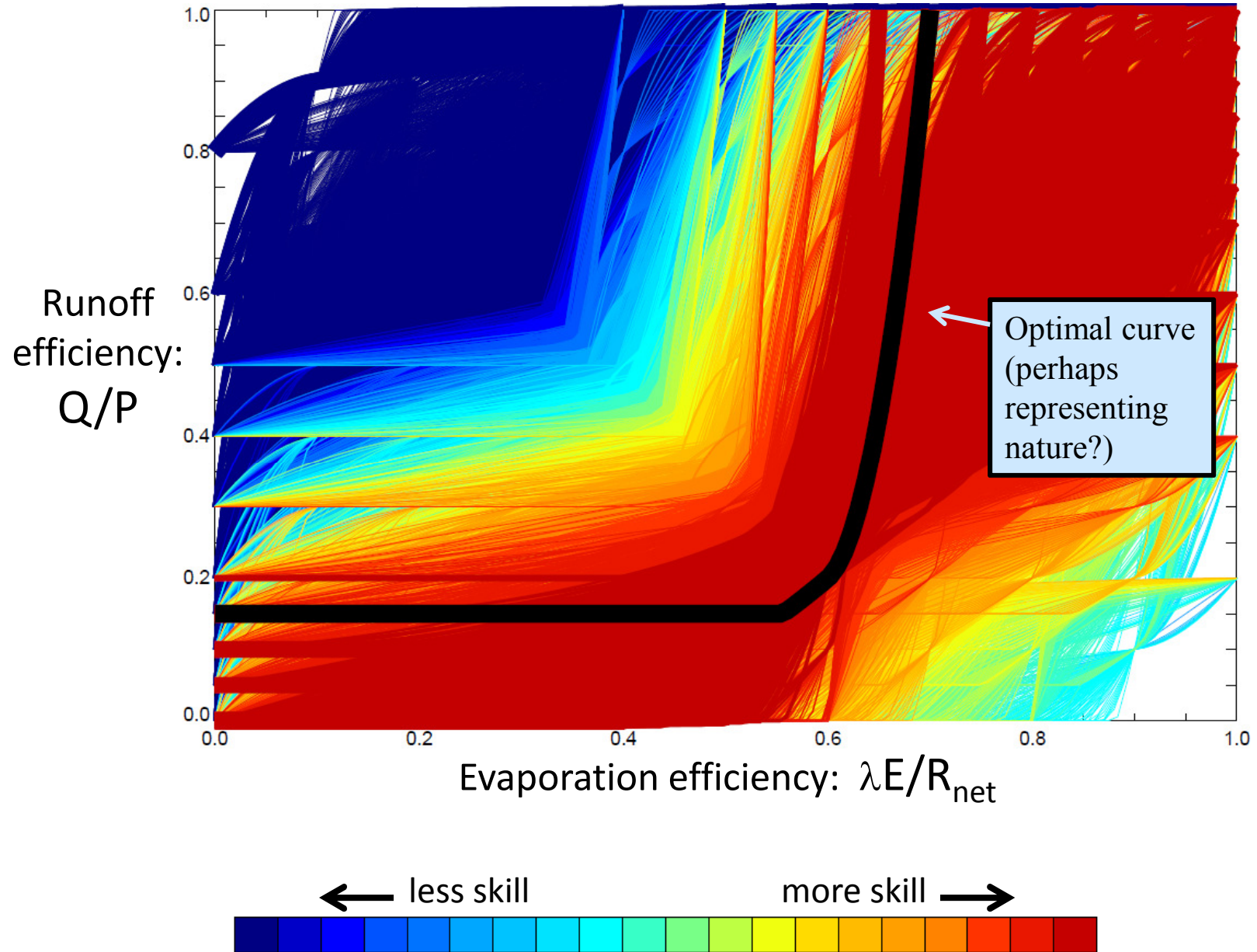




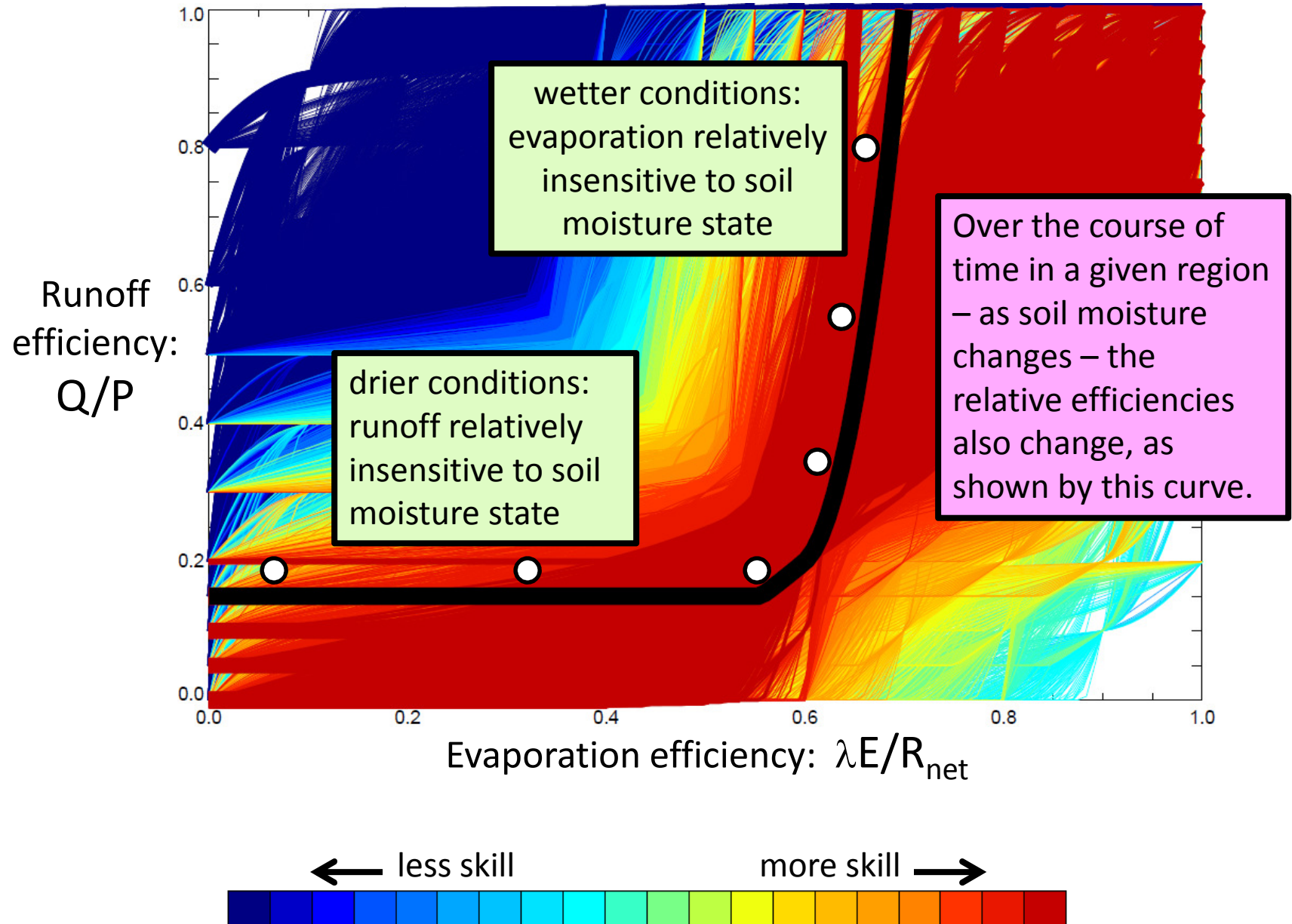
RMSE skill obtained for different curves: Upper Mississippi at Grafton



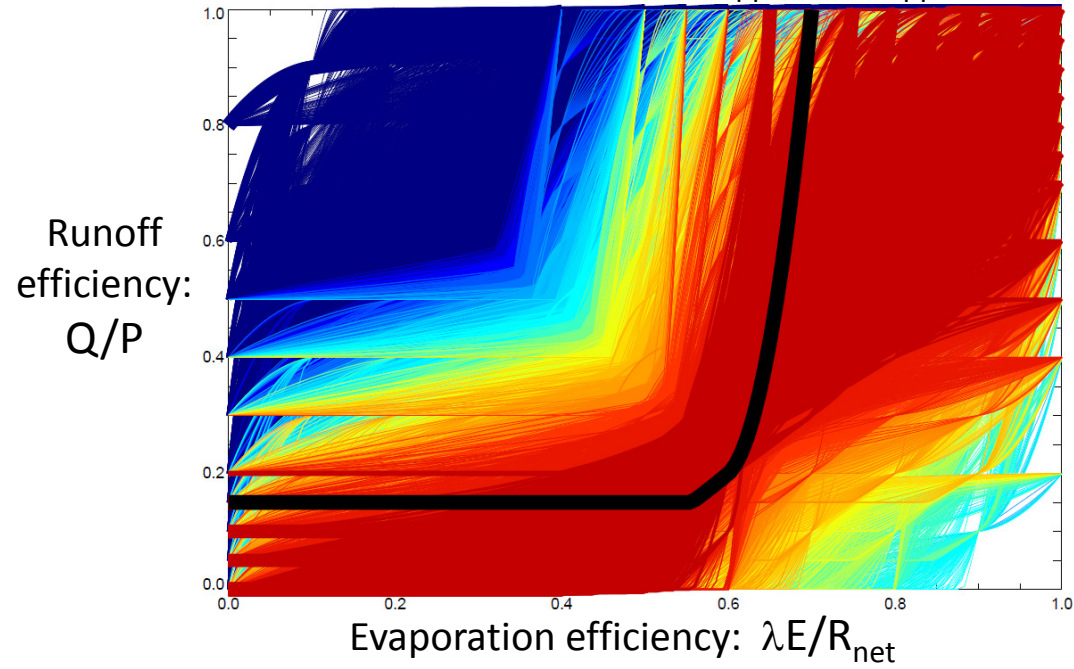
RMSE skill obtained for different curves: Upper Mississippi at Grafton



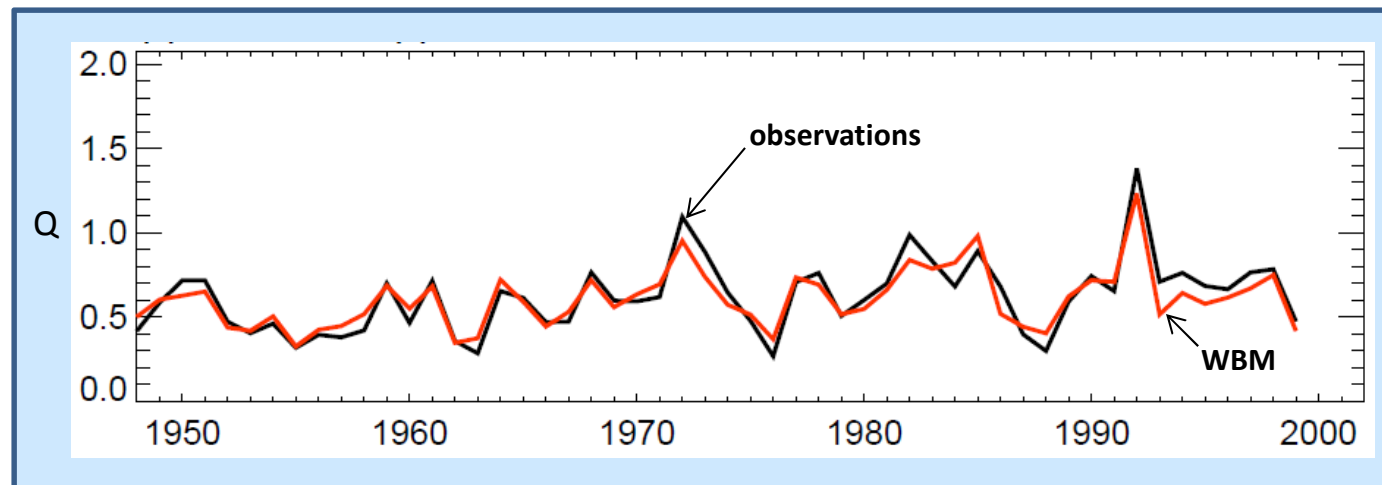
RMSE skill obtained for different curves: Upper Mississippi at Grafton



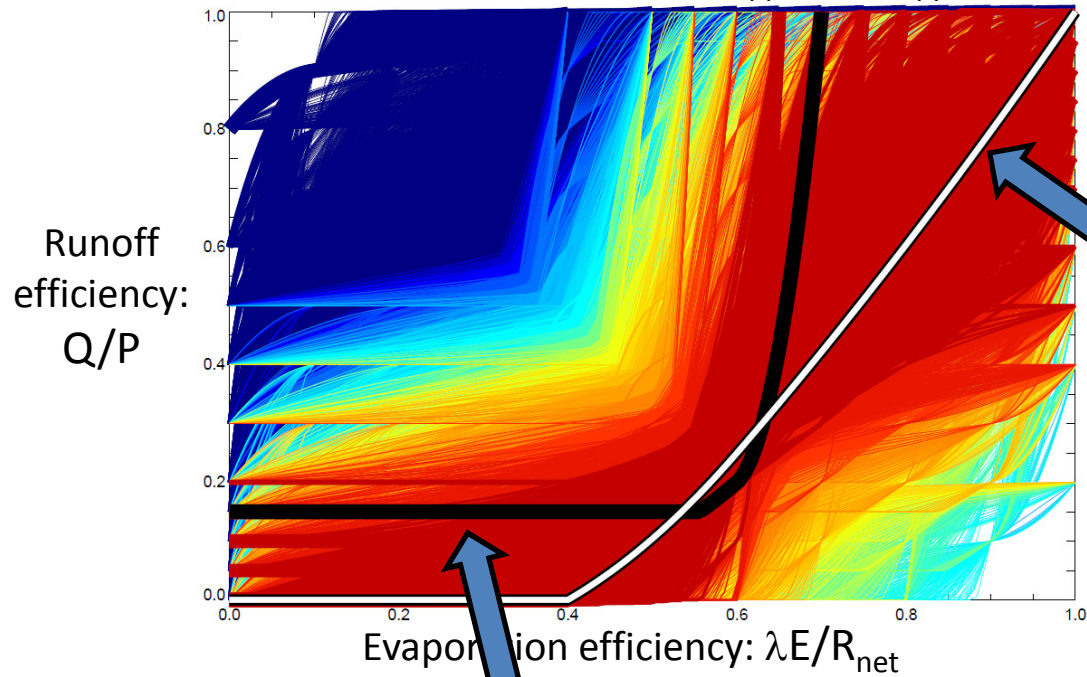
RMSE skill obtained for different curves: Upper Mississippi at Grafton



Results obtained with optimal curve

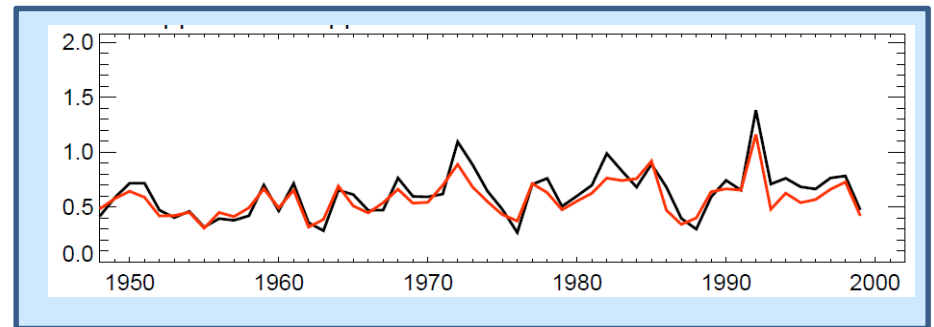
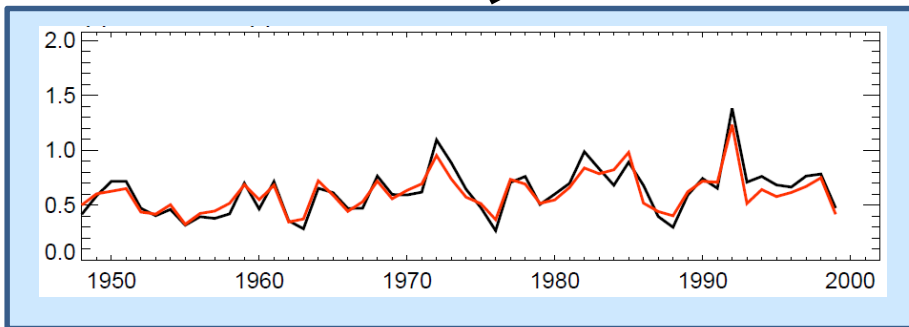


RMSE skill obtained for different curves: Upper Mississippi at Grafton



This curve looks lies largely in the “red” (high skill) zone, and it produces accurate, if not optimal, results.

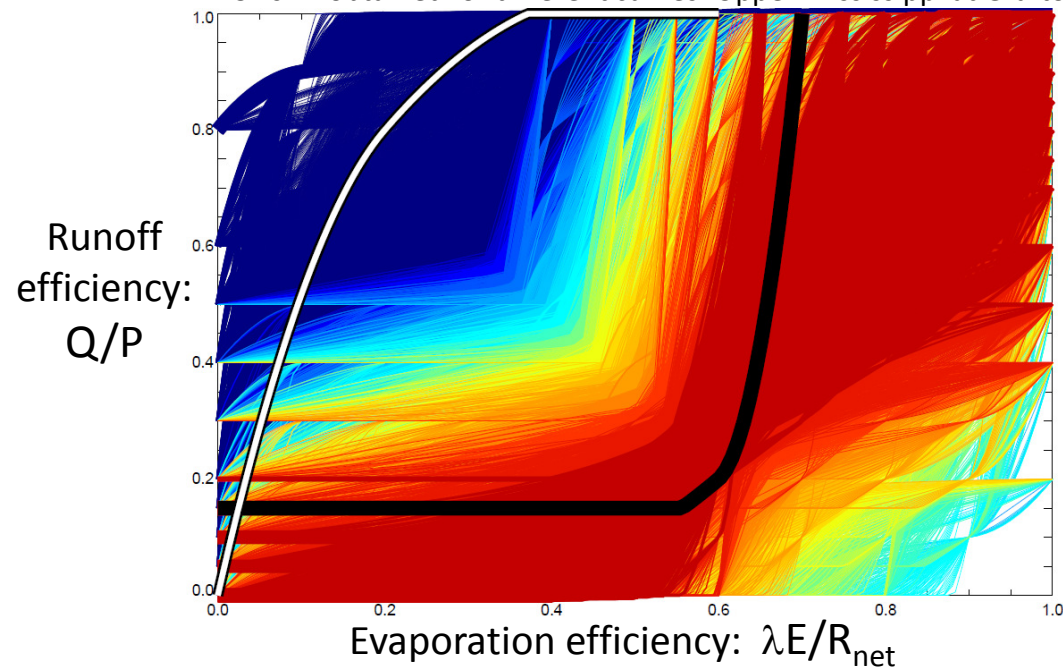
Optimal case



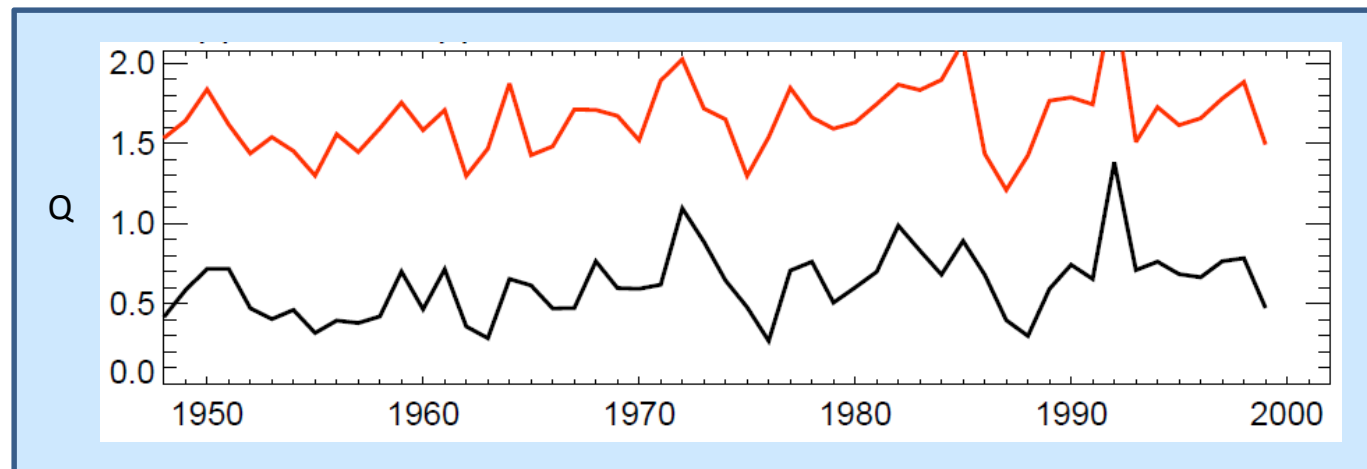
Black: observations

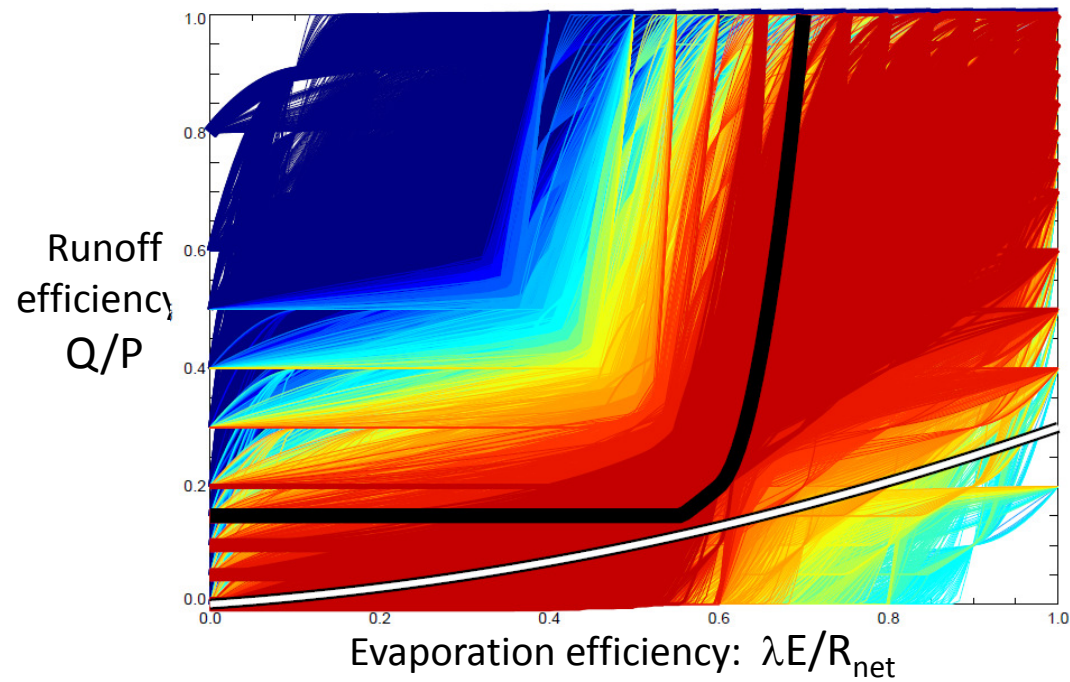
Red: model

RMSE skill obtained for different curves: Upper Mississippi at Grafton

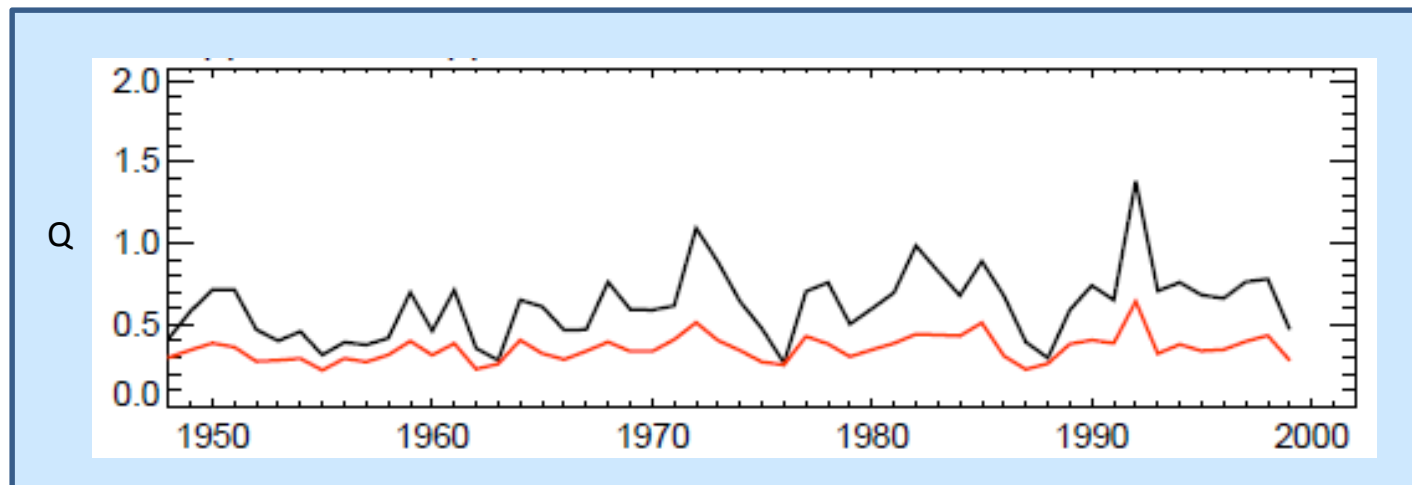


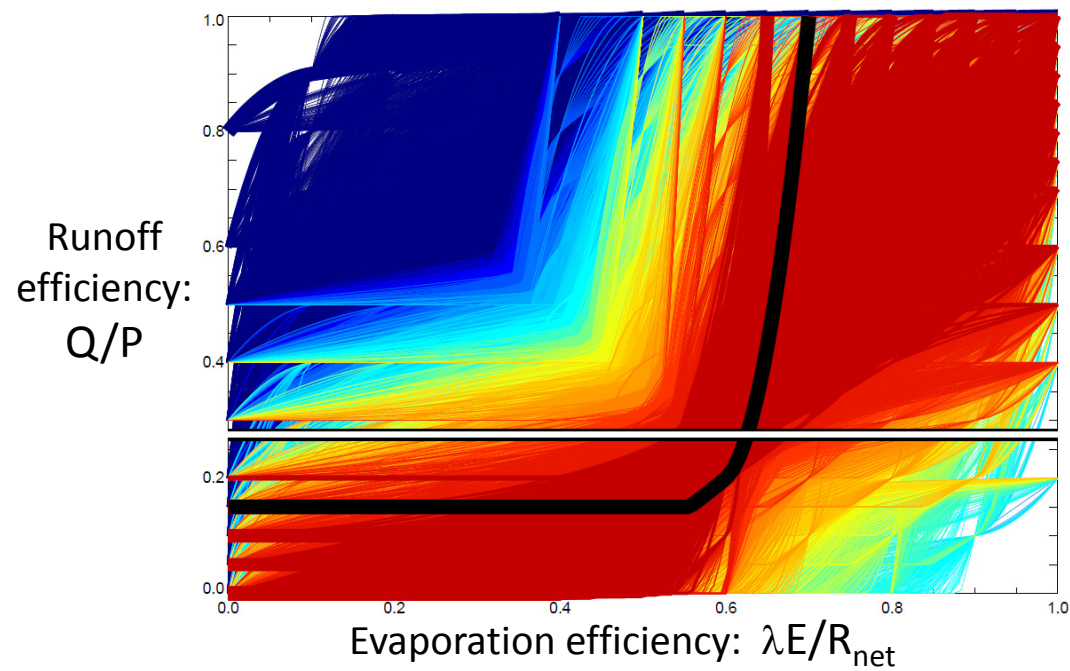
As expected, a curve lying in the northwest corner, outside the red zone, leads to overestimated runoff...



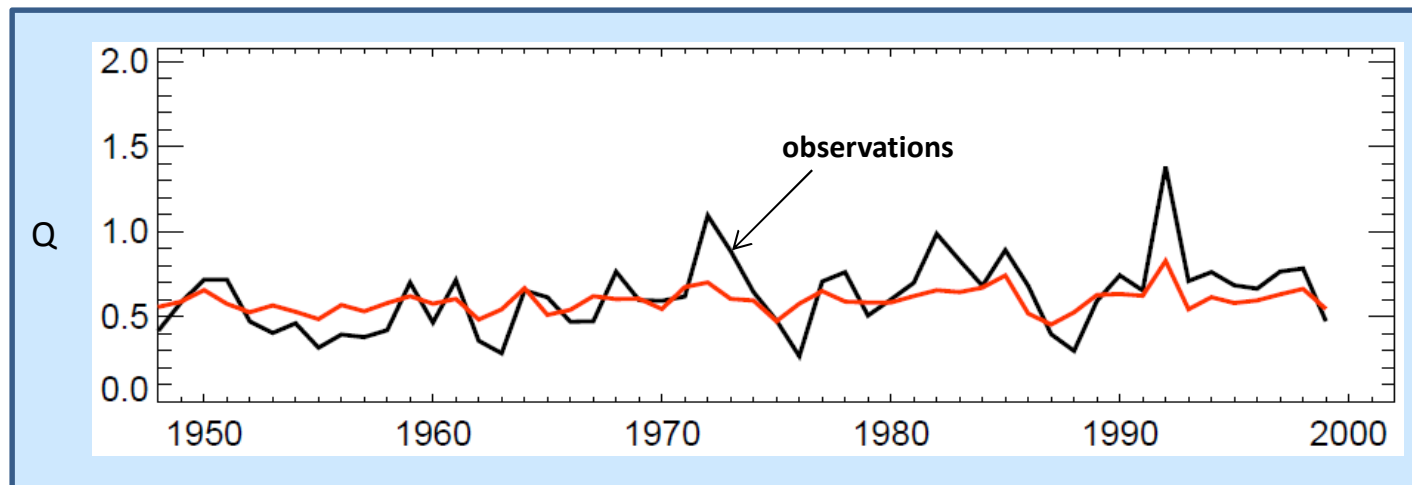


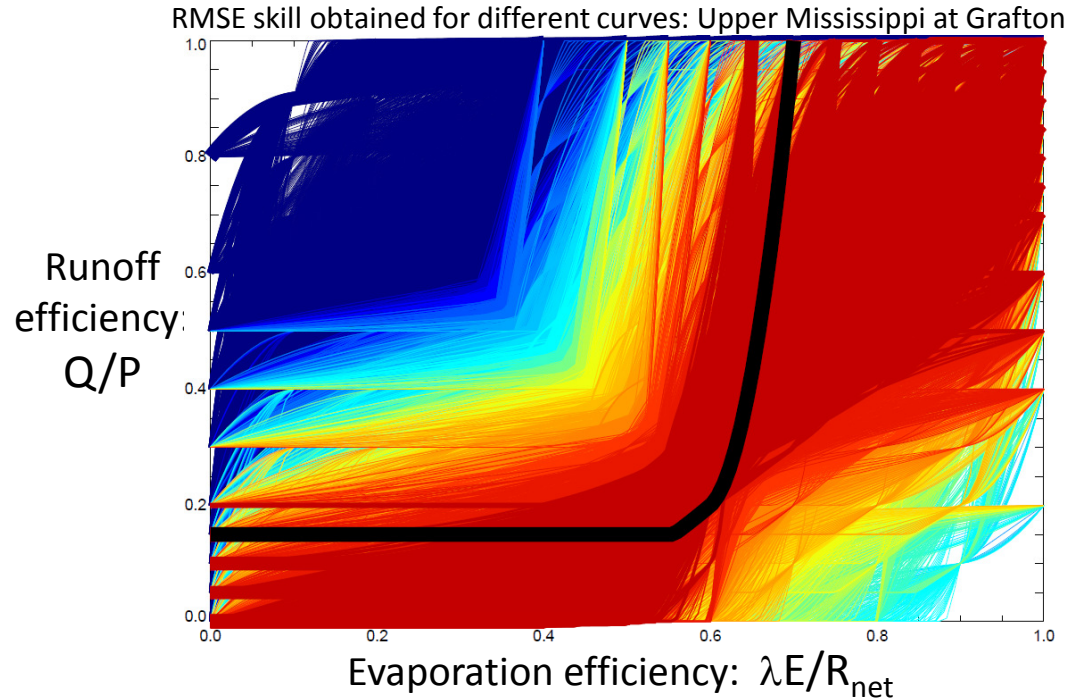
... while one in the southeast corner leads to underestimated runoff.





This example produces reasonable runoff means but low variability.





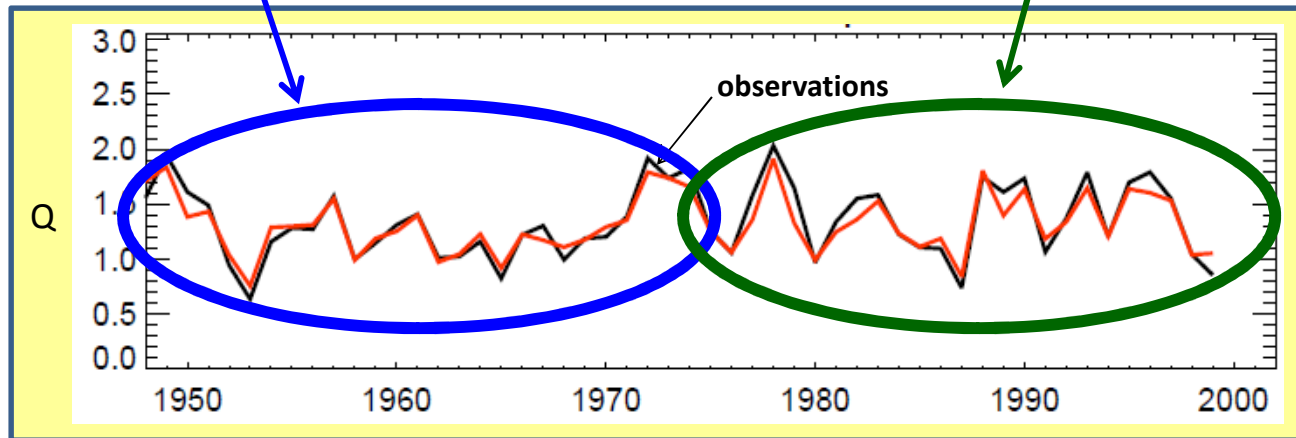
To summarize the above: By building into a simple model the evaporation and runoff efficiency relationship characterized by the black curve, we can reproduce the means and variability of observed runoff. *This suggests that the black curve – or at least a curve near it – captures something about how nature behaves. That is, **the black curve, in a sense, characterizes hydrological behavior in the basin.***

Is this result robust? Does the black curve truly represent nature? Or does it just work well because it was “fit” to work well?

One test: compute position of black curve from first half of the period; use it to simulate streamflow in the remaining half.

Fitting over the first half
of the data period alone...

... produces a WBM that performs
well in the 2nd, independent period.



42

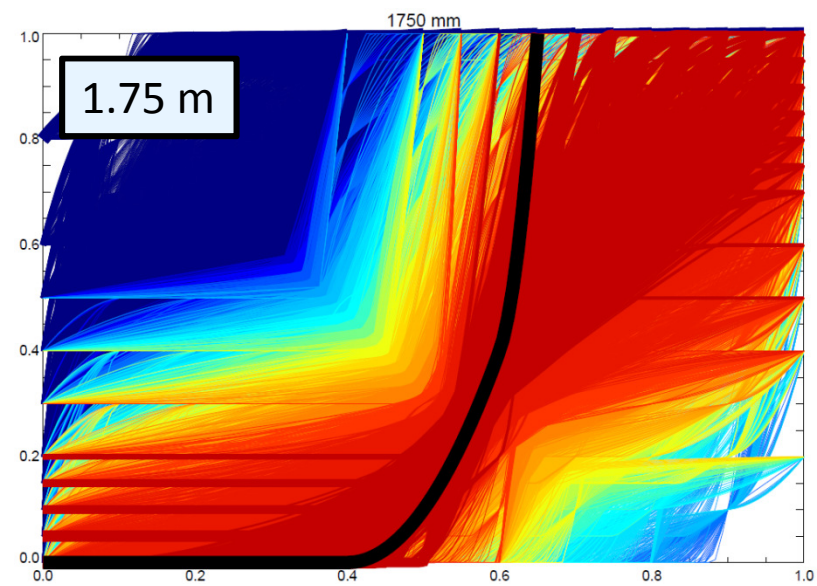
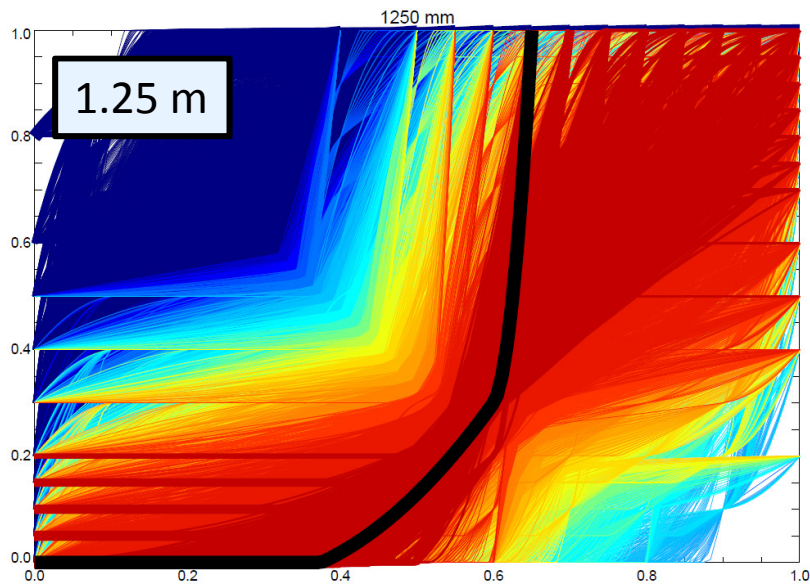
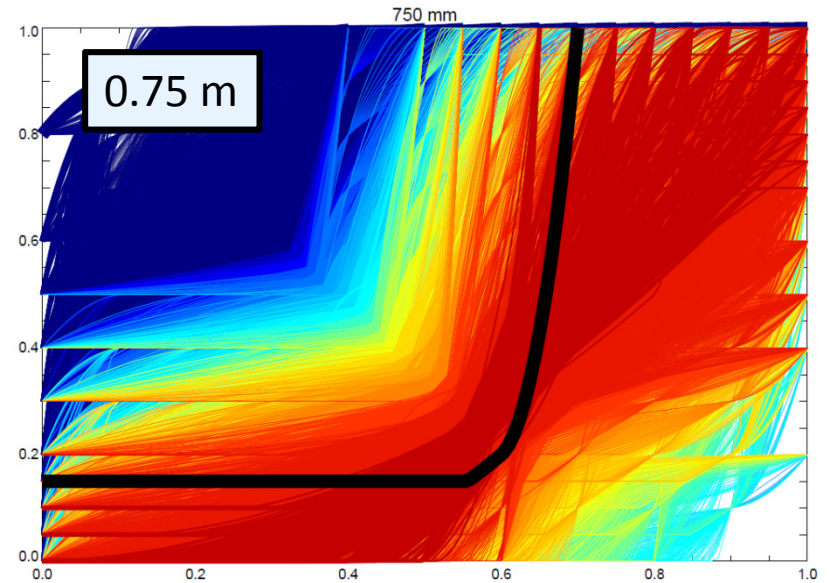
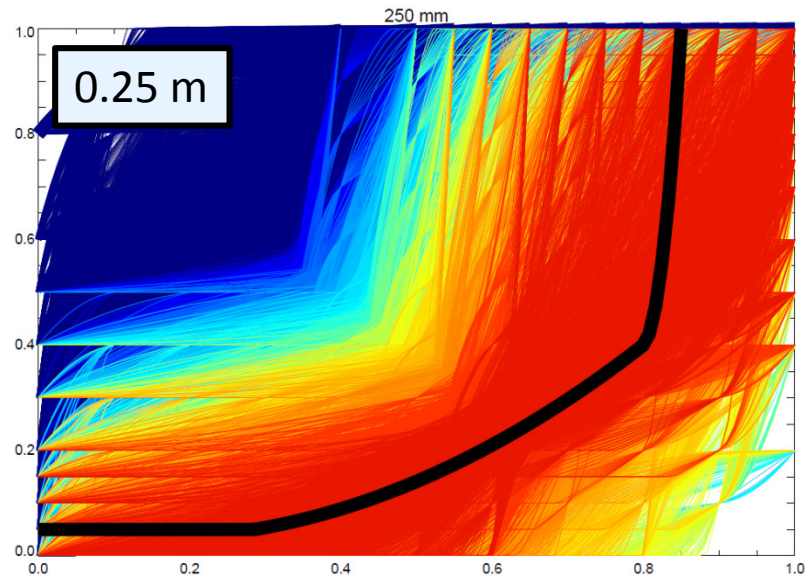
(Test was performed in all basins; these results, for the Ohio Basin, are representative. In fact, the optimal curve used here looks very much like that obtained using all the data.)

Assumed WBM Depth

The above plots assumed a depth of 0.75 m for the WBM, along with a porosity of 0.45. How sensitive are the curves found to the assumed depth?

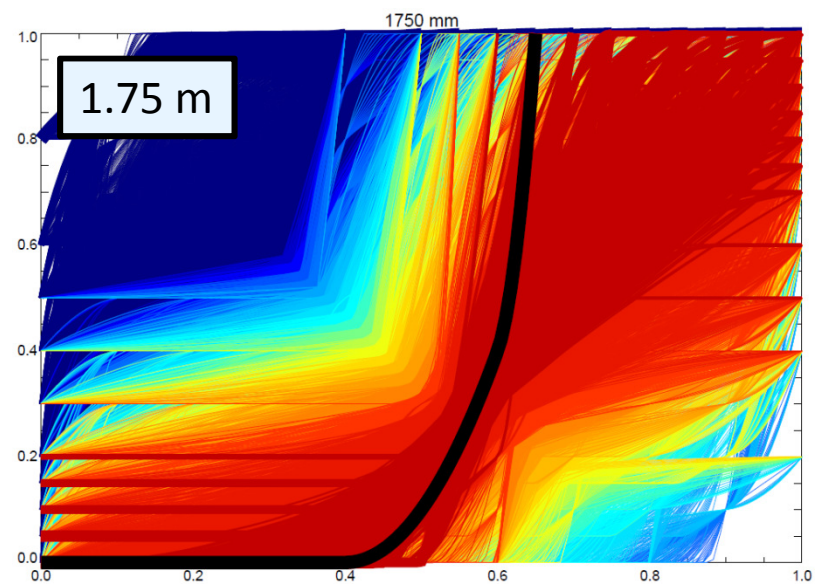
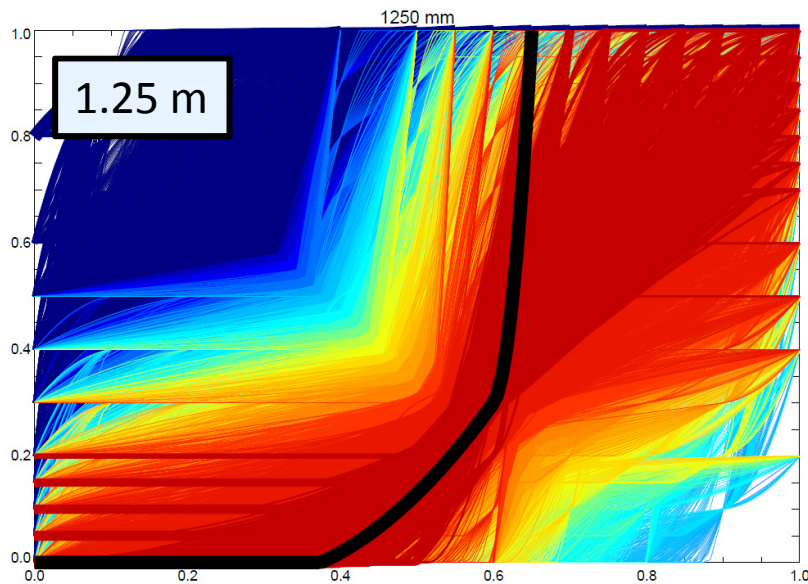
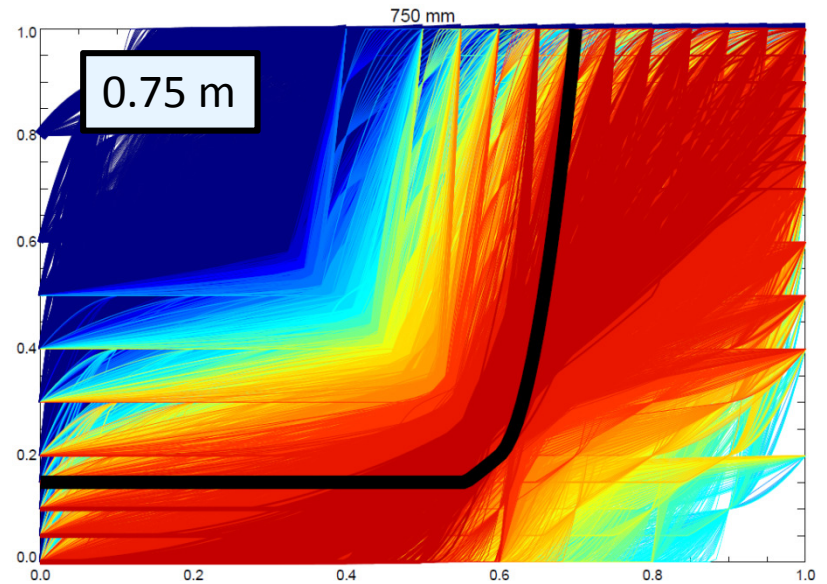
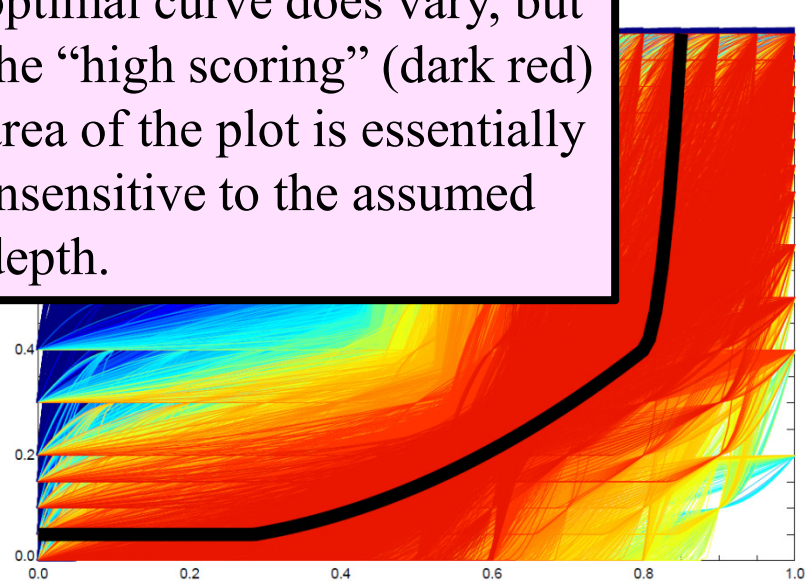
The following plot shows results for the Upper Mississippi based on four different depths...

Results for different assumed depths

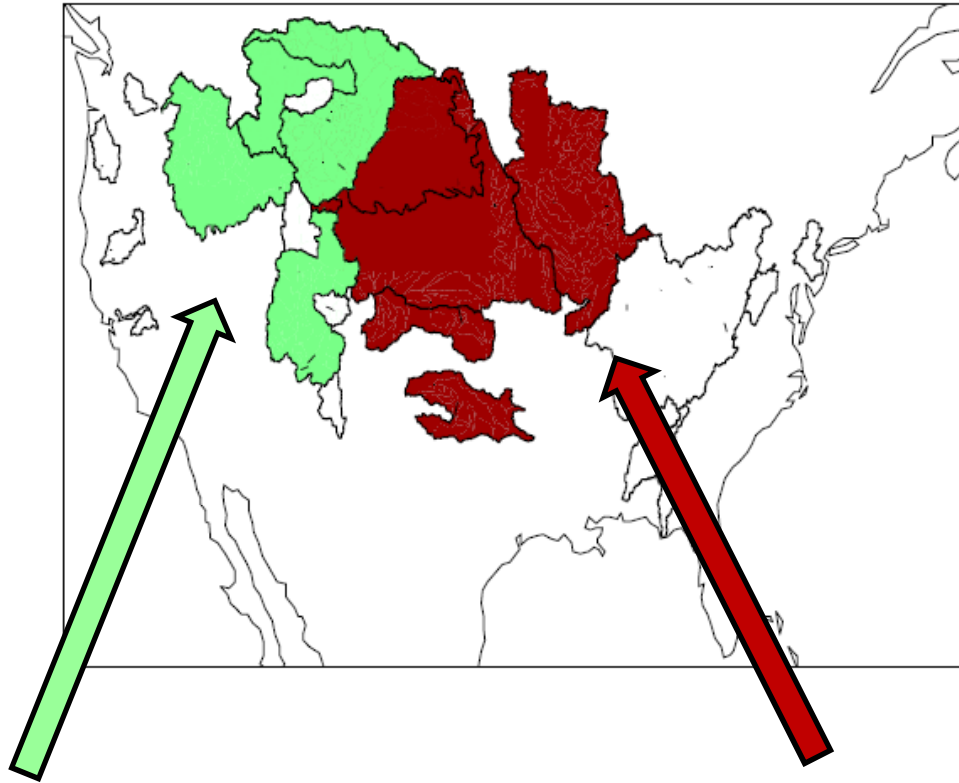


The specific position of the optimal curve does vary, but the “high scoring” (dark red) area of the plot is essentially insensitive to the assumed depth.

for different assumed depths



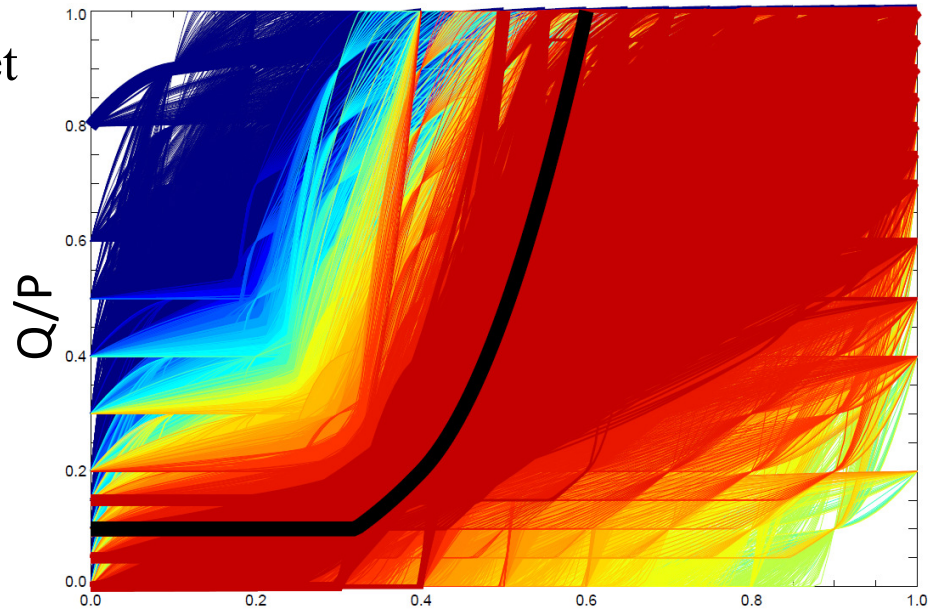
Variation of curve with location



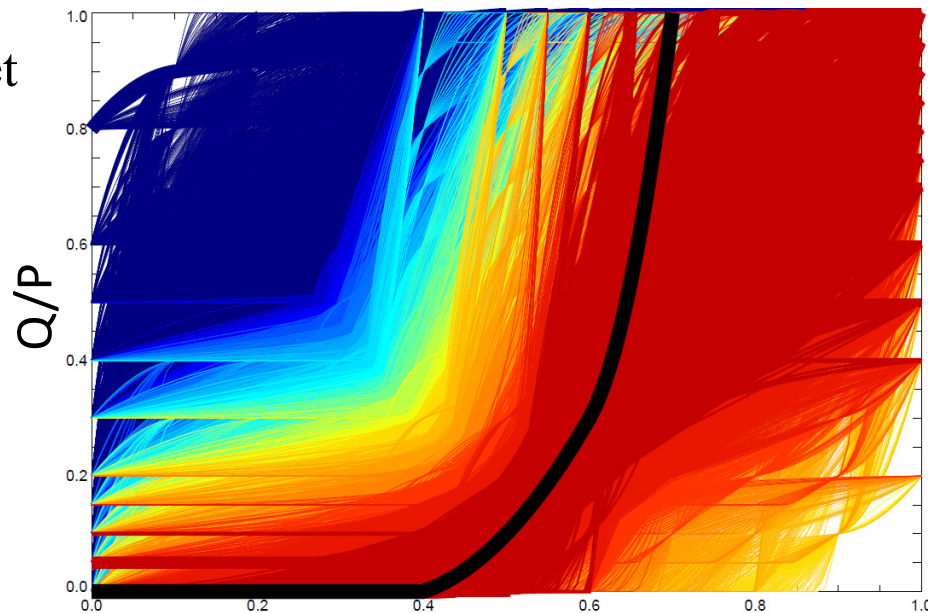
Consider a set of large
and (relatively)
mountainous basins...

...versus a set of
large and (relatively)
flat basins

RMSE skill obtained for set
of mountainous basins



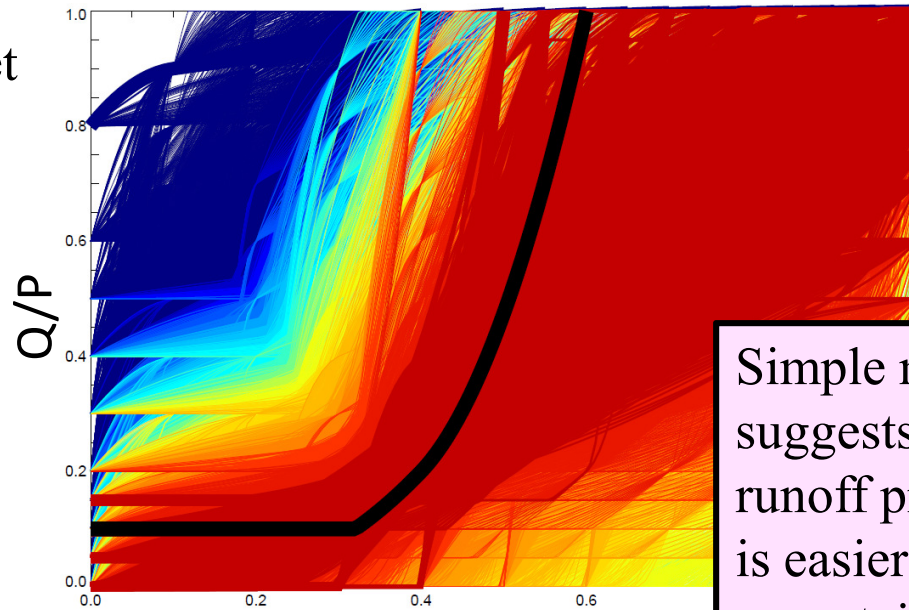
RMSE skill obtained for set
of flat basins



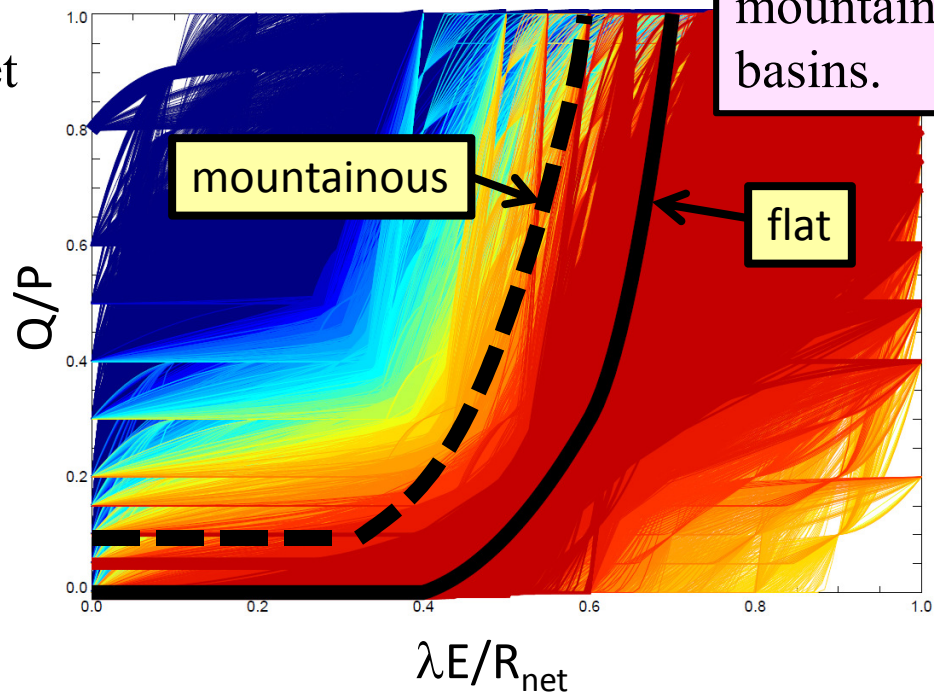
(assumes depth = 0.75m)

$\lambda E/R_{\text{net}}$

RMSE skill obtained for set
of mountainous basins



RMSE skill obtained for set
of flat basins

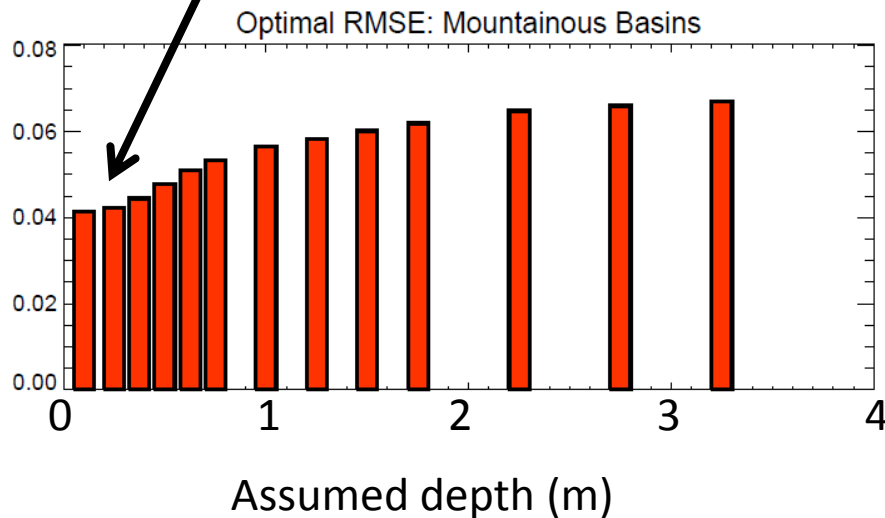


Simple model
suggests that
runoff production
is easier for more
mountainous
basins.

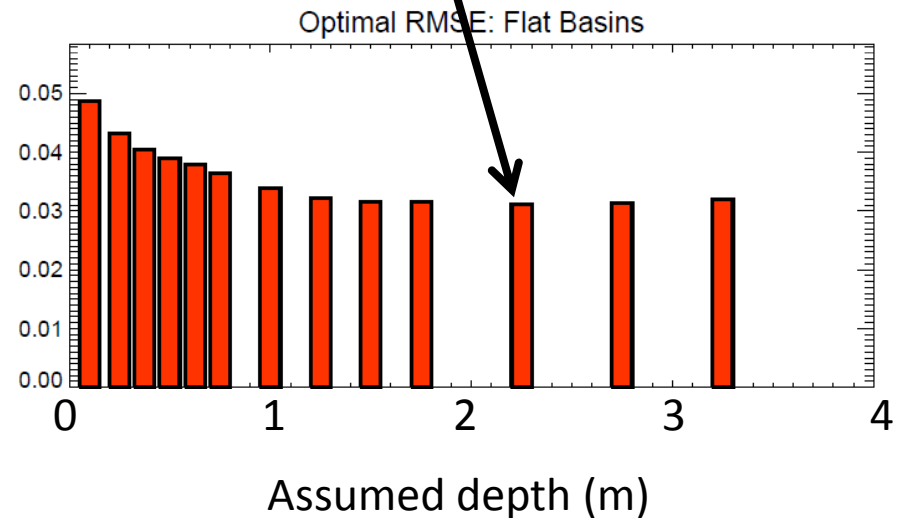
(assumes depth = 0.75m)

What about optimal depths for mountainous vs. flat regions?

In mountainous basins, the best results are obtained with shallow depths



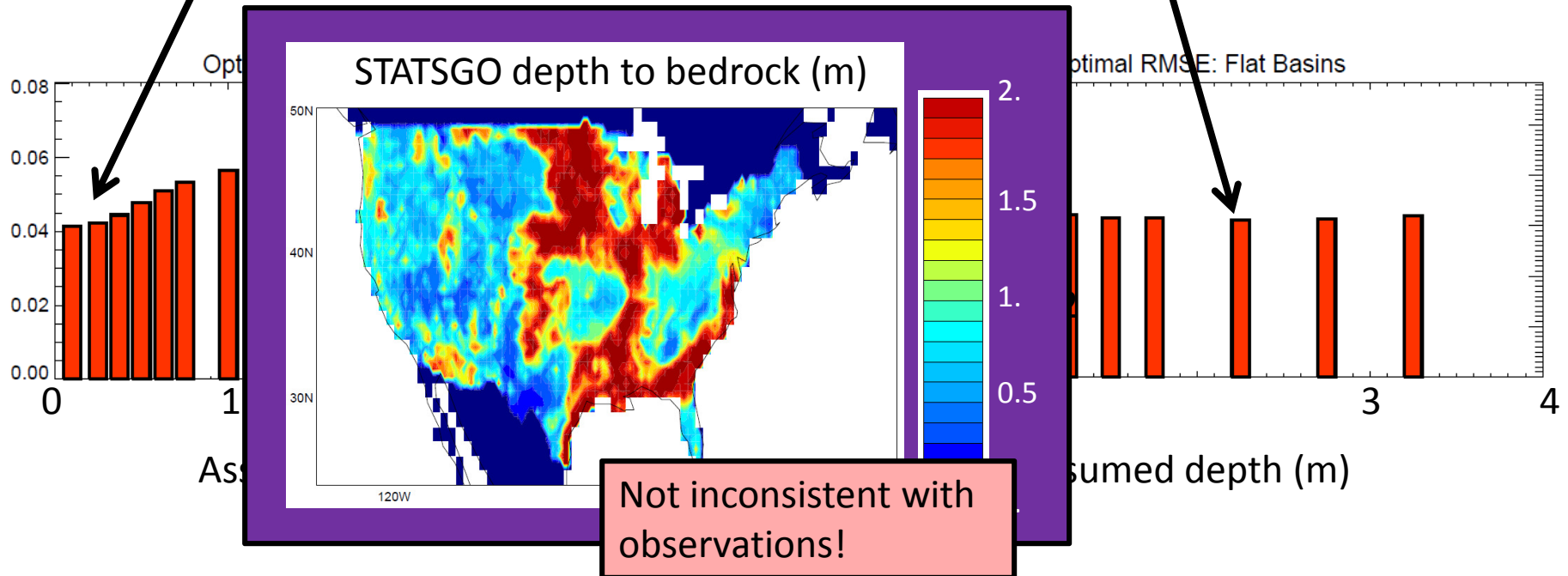
In flatter basins, the best results are obtained with 2m (or higher) depth.



What about optimal depths for mountainous vs. flat regions?

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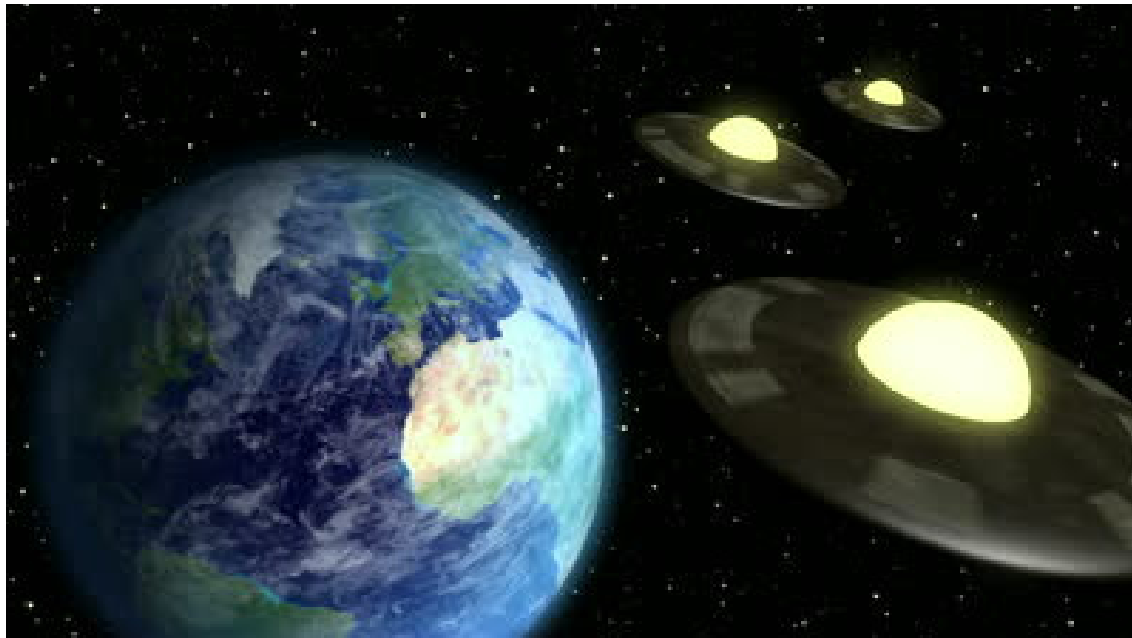
In flatter basins, the best results are obtained with 2m (or higher) depth.



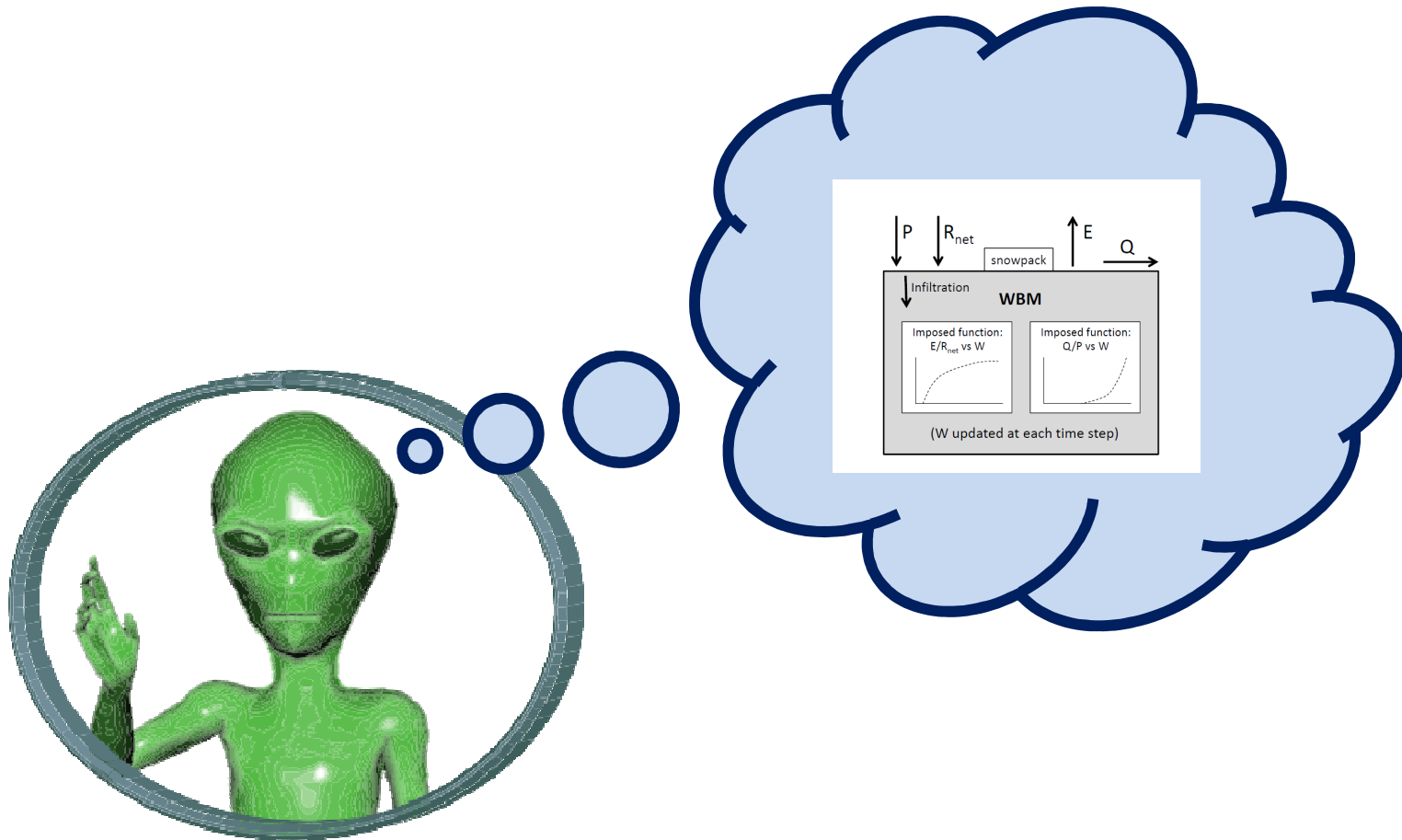
Another way to look at these results (please bear with me!)

Suppose some visiting aliens, wanting to avoid direct contact with humans, secretly monitored precipitation, net radiation, and streamflow from cloaked ships in space.

What “hidden” features about Earth’s hydrology could they infer?

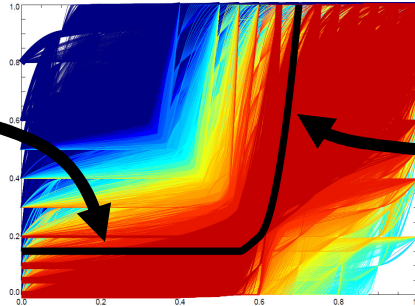


Make assumption: if they are intelligent enough for interstellar flight, they would consider using a simple water balance model.

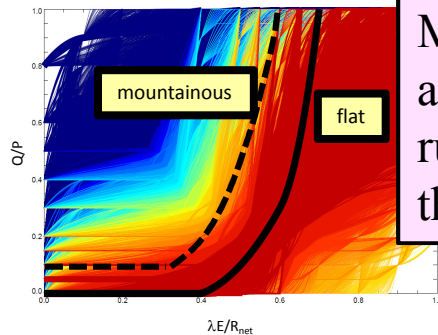


As described above, *based solely on streamflow, precipitation, and net radiation measurements*, they could infer that:

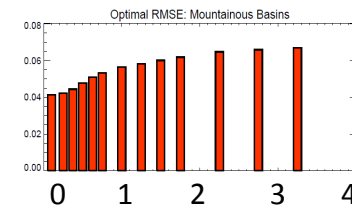
Evaporation is more sensitive to soil moisture variation in the dry regime...



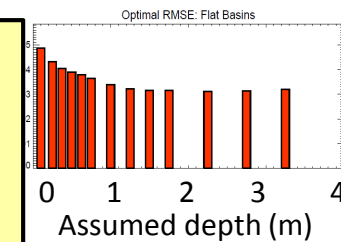
...whereas runoff is more sensitive to soil moisture in the wet regime.



Mountainous areas generate runoff more easily than flatter areas.



Mountainous areas have smaller effective depths than flatter areas.



Outline of talk

1. Efficiency relationships
- 2. The “Budyko-istic” perspective**
3. Relevance to land surface model development
4. Soil moisture: Nature’s linchpin

Broader picture – a salute to M.I. Budyko, who pioneered the analysis of energy and water availability on evaporation and runoff.

Budyko's equation is:

$$E = \left[\frac{RP}{\lambda} \tanh \frac{P\lambda}{R} \left(1 - \cosh \frac{R}{P\lambda} + \sinh \frac{R}{P\lambda} \right) \right]^{1/2}$$

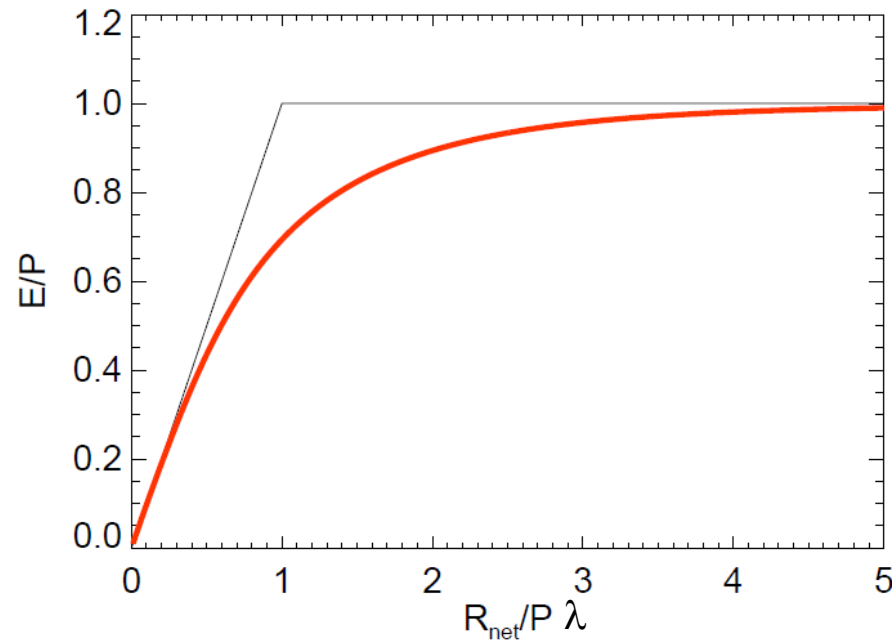
← based on joint controls of energy and water availability on evaporation

or

$$\lambda E / R_{\text{net}} = f(D), \quad \text{where } D \text{ is the dryness index, } R_{\text{net}} / \lambda P.$$



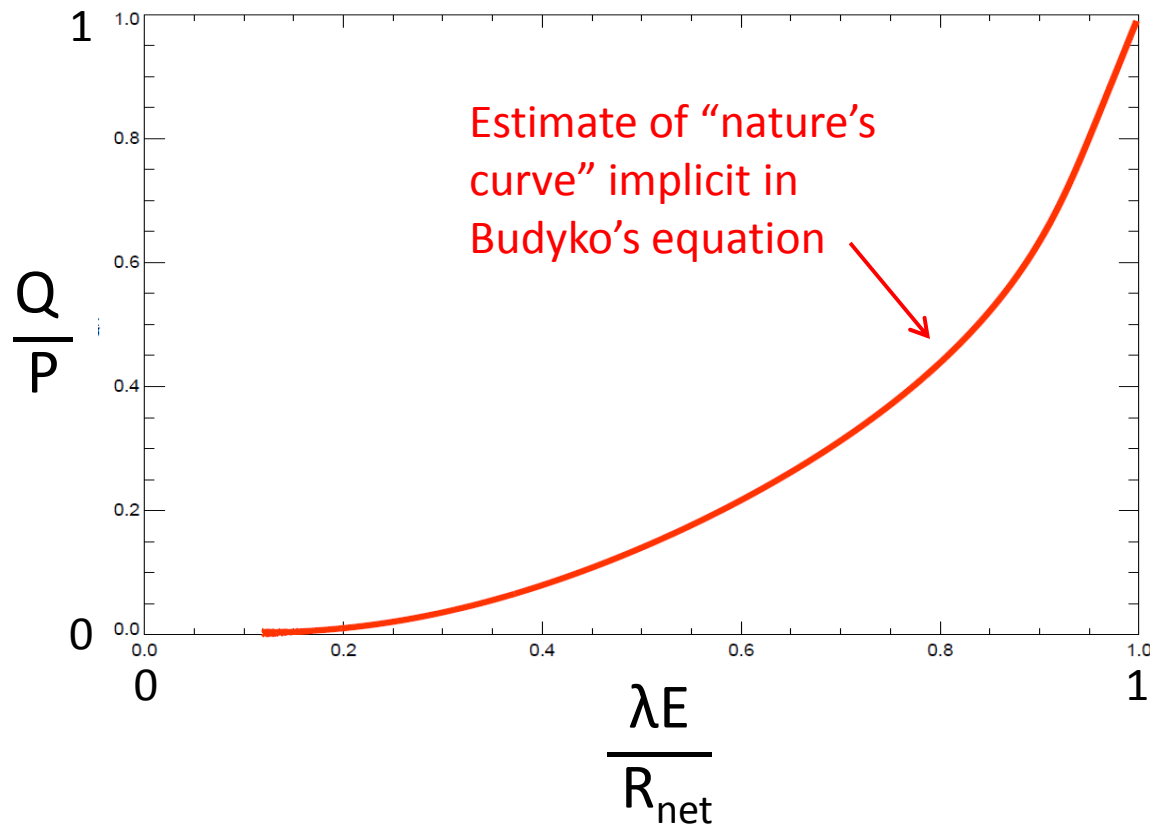
Usual depiction of
Budyko's relationship \Rightarrow



Note that from Budyko, we have $\lambda E / R_{\text{net}} = f(D)$

Using $Q = P - E$, this can be rearranged to form $Q / P = 1 - D f(D)$.

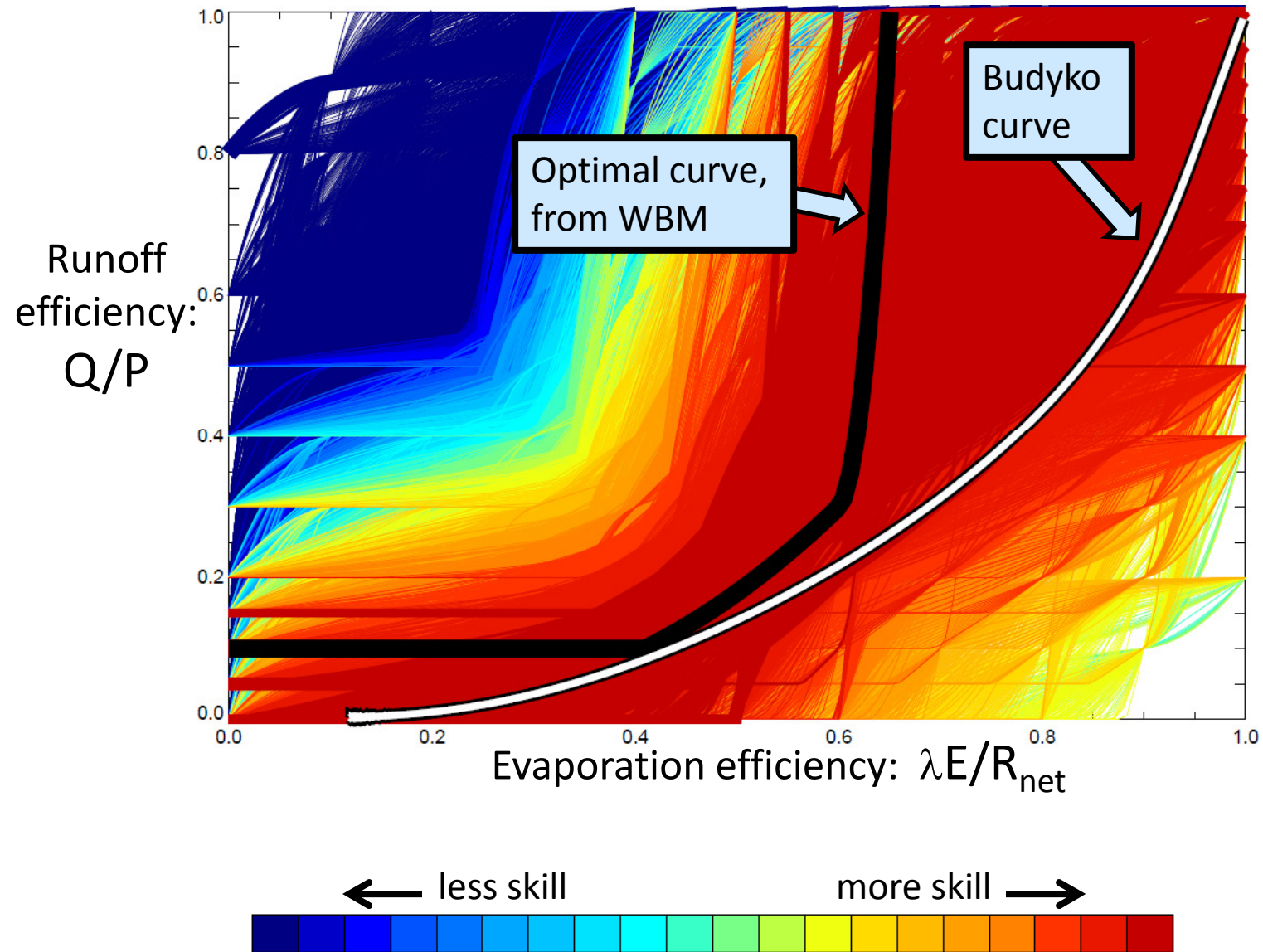
By using a number of D values, we can reconstruct a relationship between $\lambda E/R_{\text{net}}$ and Q/P .



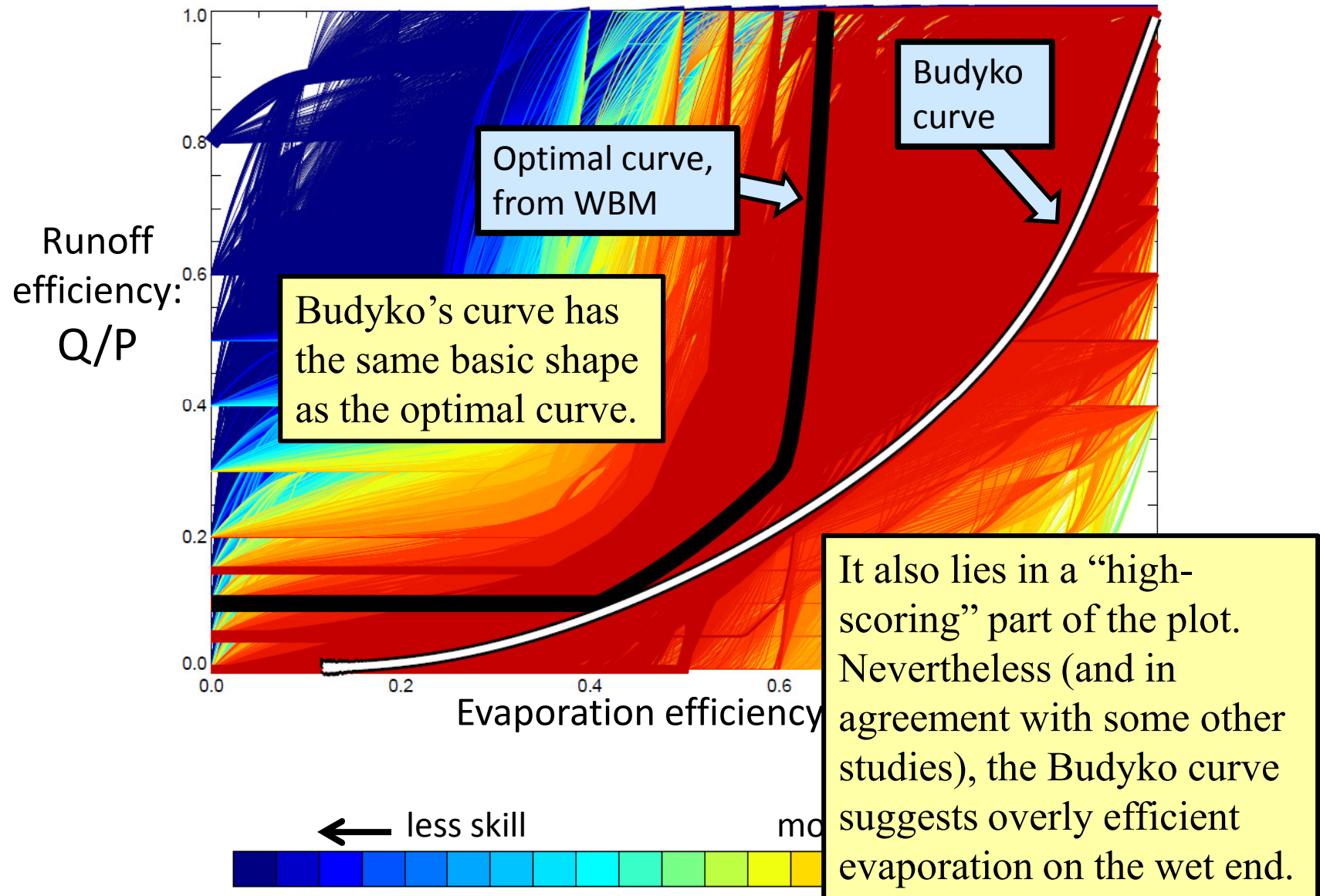
How does Budyko's effective curve compare with what comes out of the present analysis, which is based on water balance modeling?

(Note: Budyko focused on long-term climatic means rather than short-term efficiencies; still, the curve is of interest...)

Skill plot considering all basins (not just one, as in previous slides)



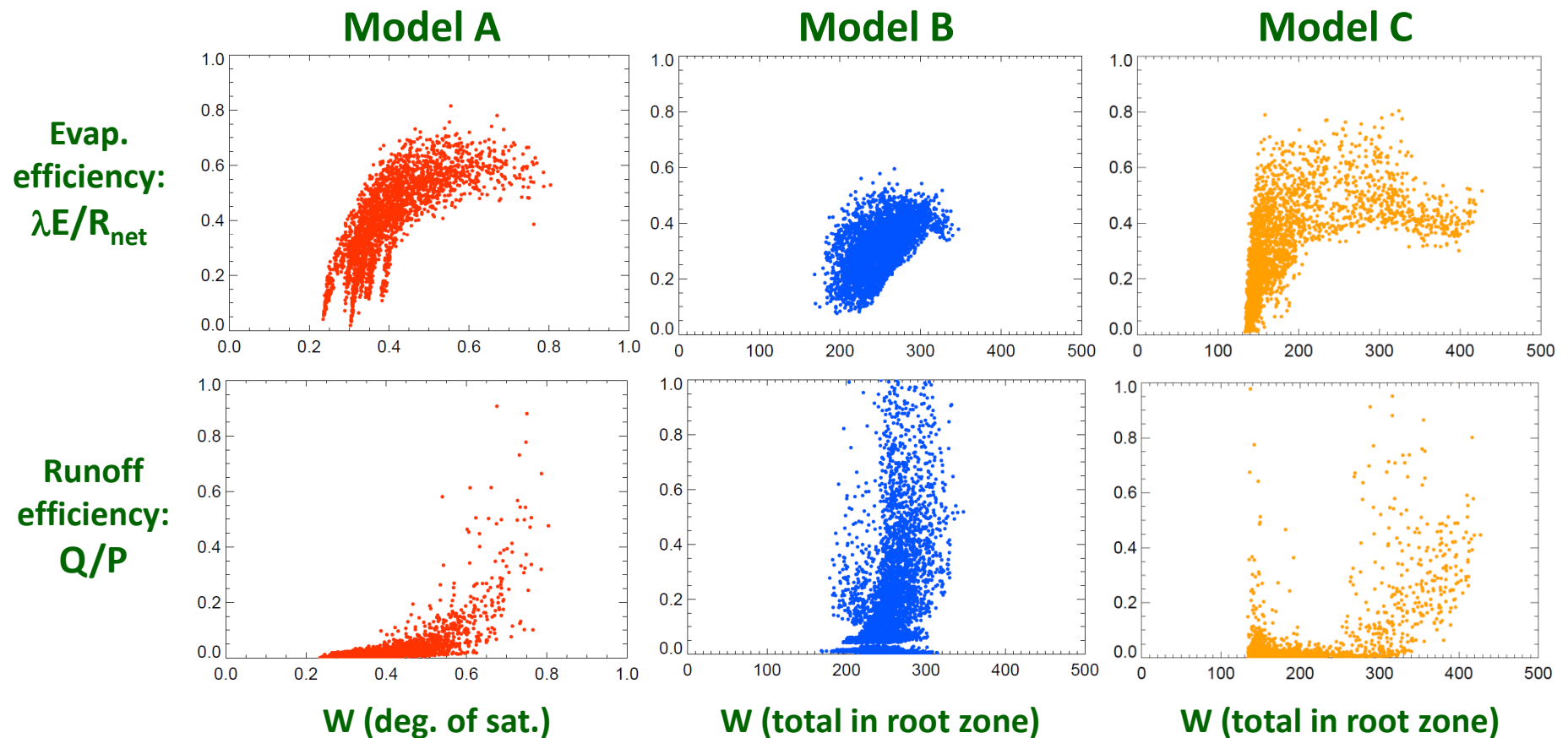
Skill plot considering all basins (not just one, as in previous slides)



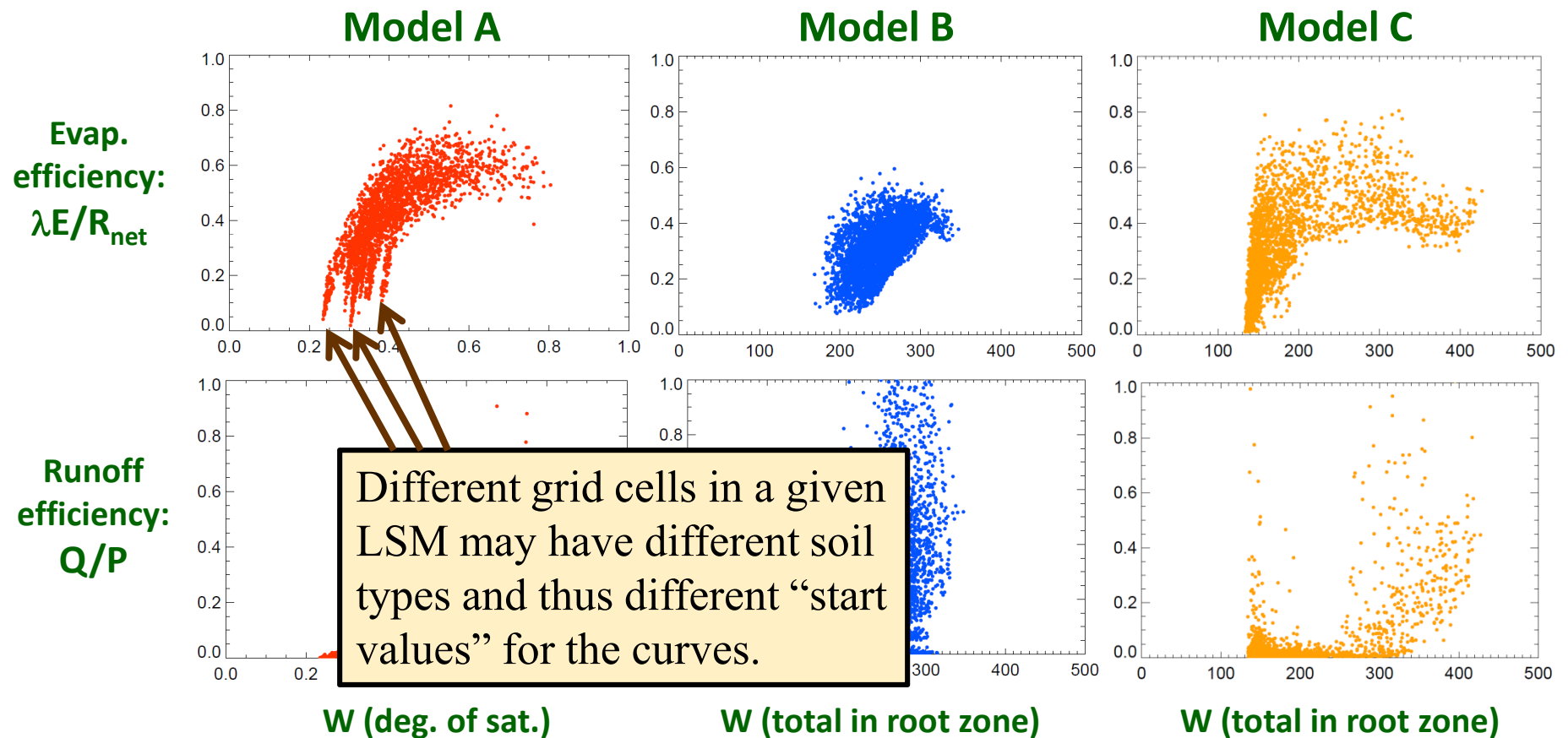
Outline of talk

1. Efficiency relationships
2. The “Budyko-istic” perspective
- 3. Relevance to land surface model development**
4. Soil moisture: Nature’s linchpin

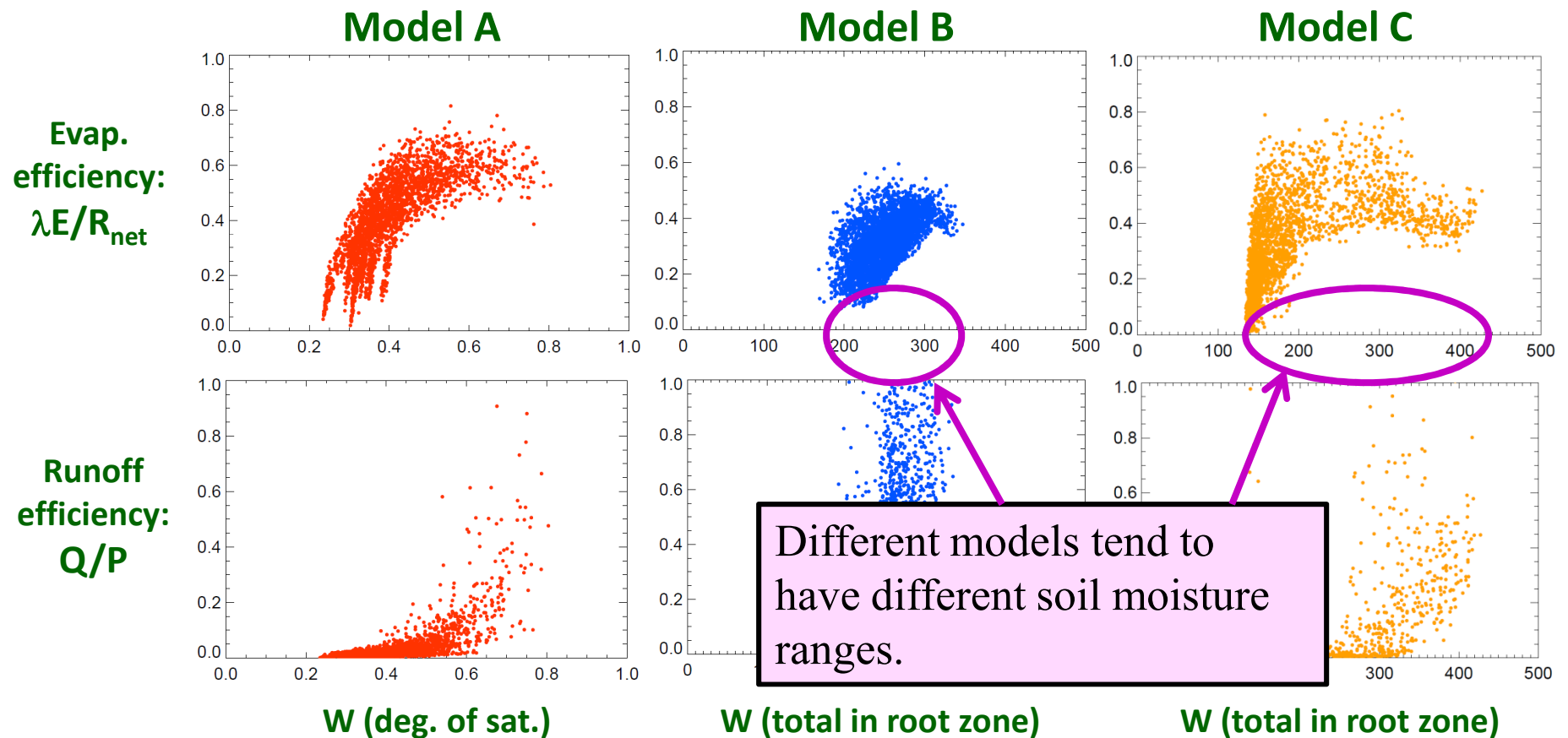
Model-specific nature of the soil moisture variable in a given land surface model (LSM) makes the evaluation and intercomparison of LSM evaporation and runoff treatments difficult.



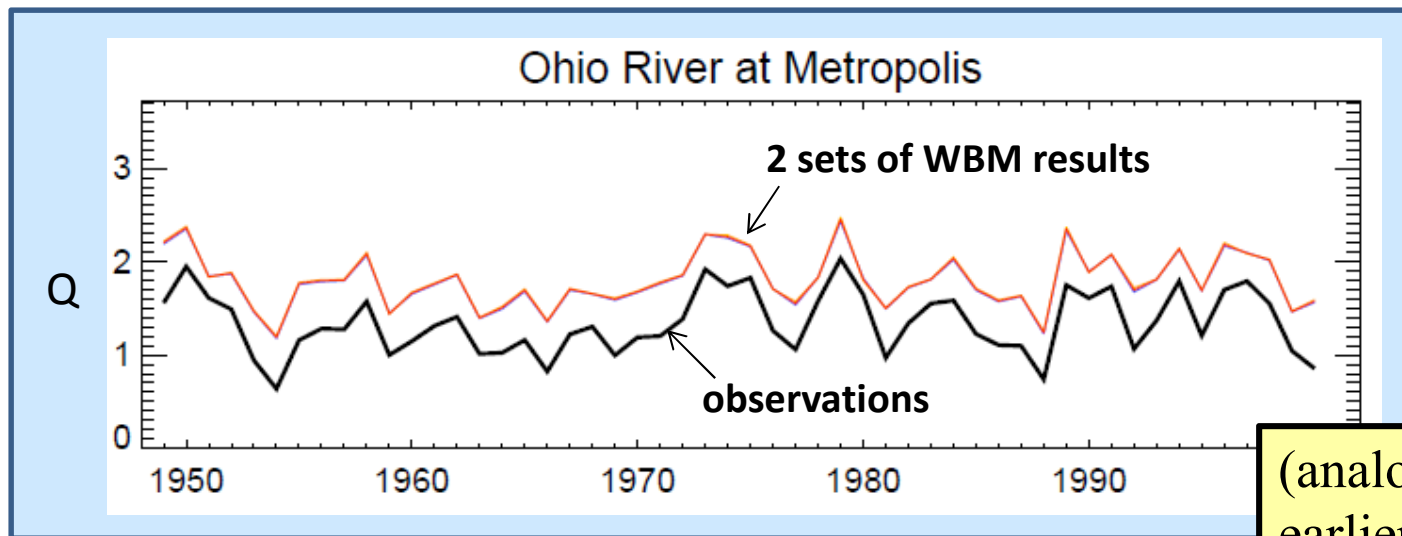
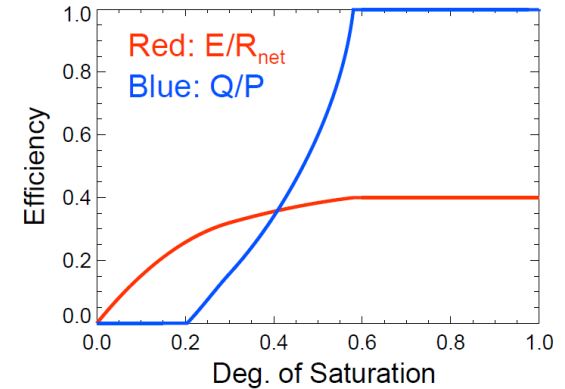
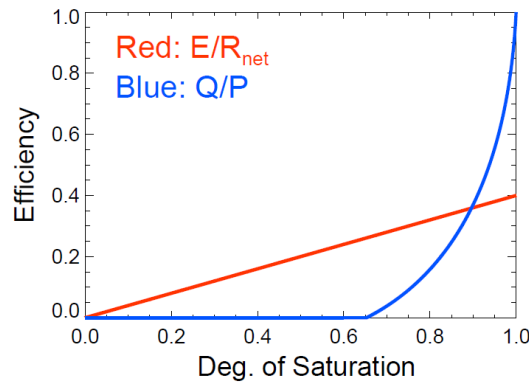
Model-specific nature of the soil moisture variable in a given land surface model (LSM) makes the evaluation and intercomparison of LSM evaporation and runoff treatments difficult.



Model-specific nature of the soil moisture variable in a given land surface model (LSM) makes the evaluation and intercomparison of LSM evaporation and runoff treatments difficult.



Most importantly, as suggested by the WBM, models with very different functions may produce essentially identical fluxes.



(analogous to earlier slide)

Recall this talk's hypothesis:

Analysis with the WBM supports the idea that hydrological behavior is controlled as much by

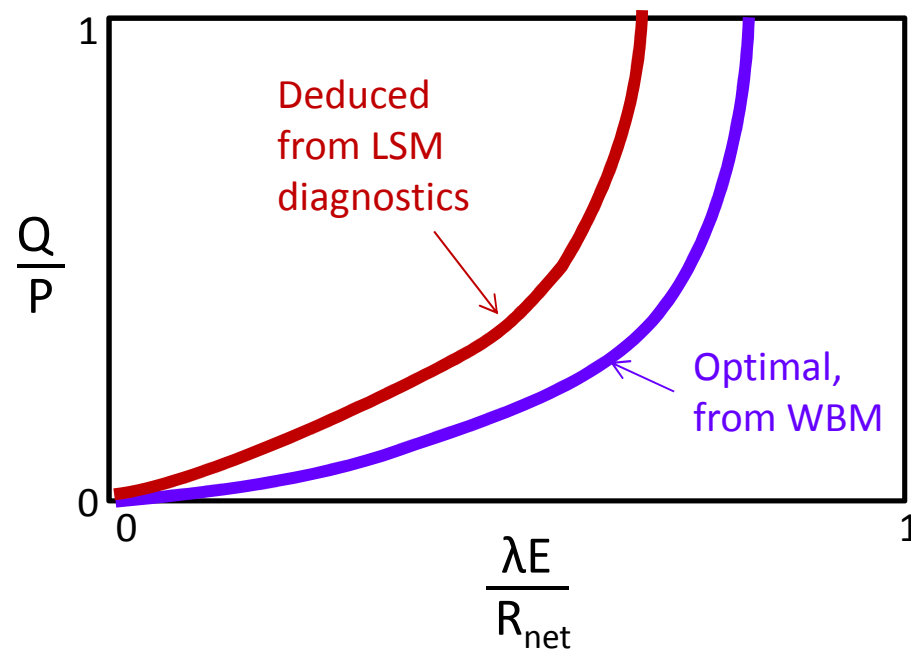
$$\lambda E/R_{\text{net}} \text{ vs. } Q/P$$

as by

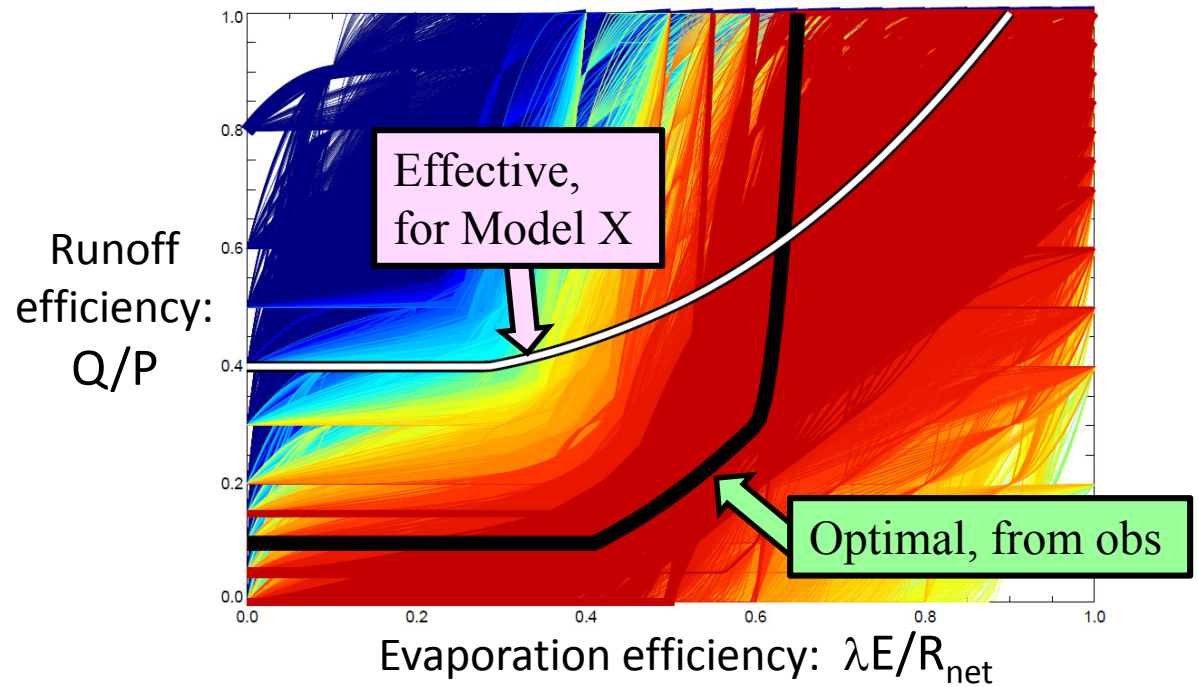
$$\lambda E/R_{\text{net}} \text{ vs. } W \text{ and } Q/P \text{ vs. } W$$

Relevance to Land Surface Model Development

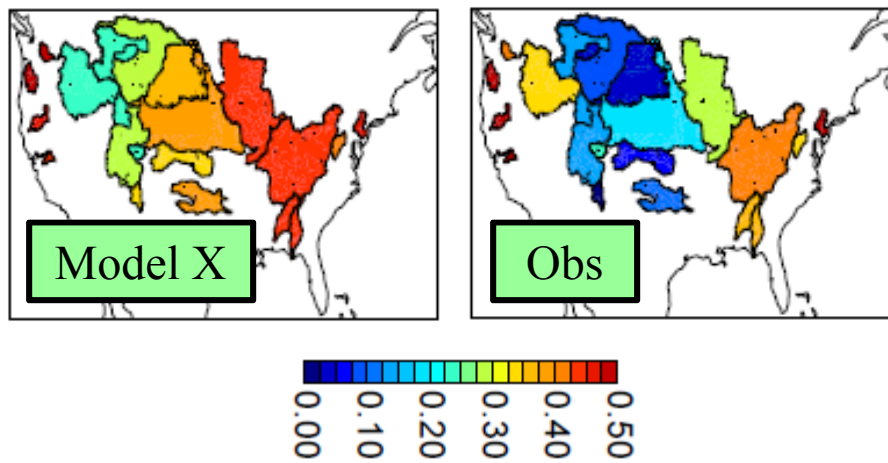
Taking soil moisture out of the problem – examining an LSM's evaporation efficiency vs. runoff efficiency relationship directly – greatly simplifies the evaluation of the LSM.



Consider “Model X”
(an actual land surface
model). Analysis of
CONUS simulations
produced by Model X
leads to an estimate of
its effective curve.

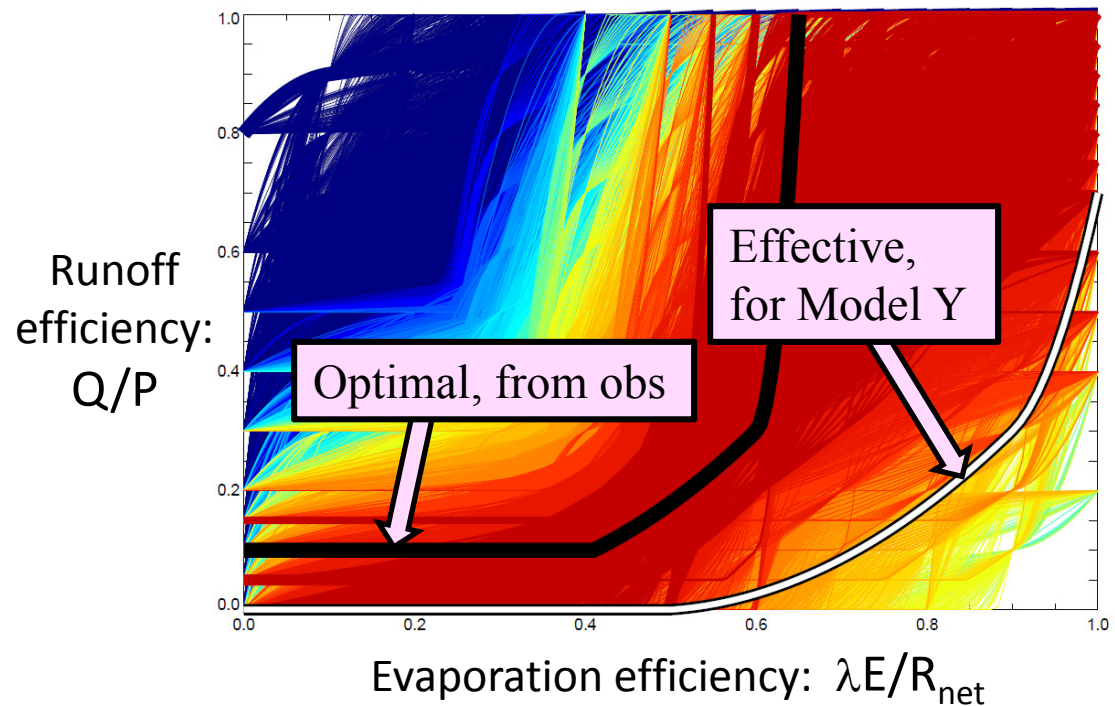


Annual mean Q / Annual mean P

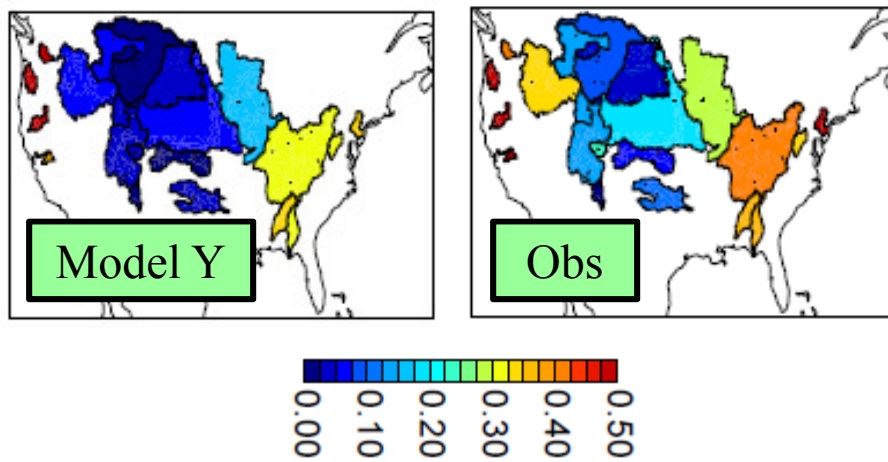


Sure enough, Model X
tends to overestimate
runoff ratios.

Now consider a different actual model, “Model Y”.

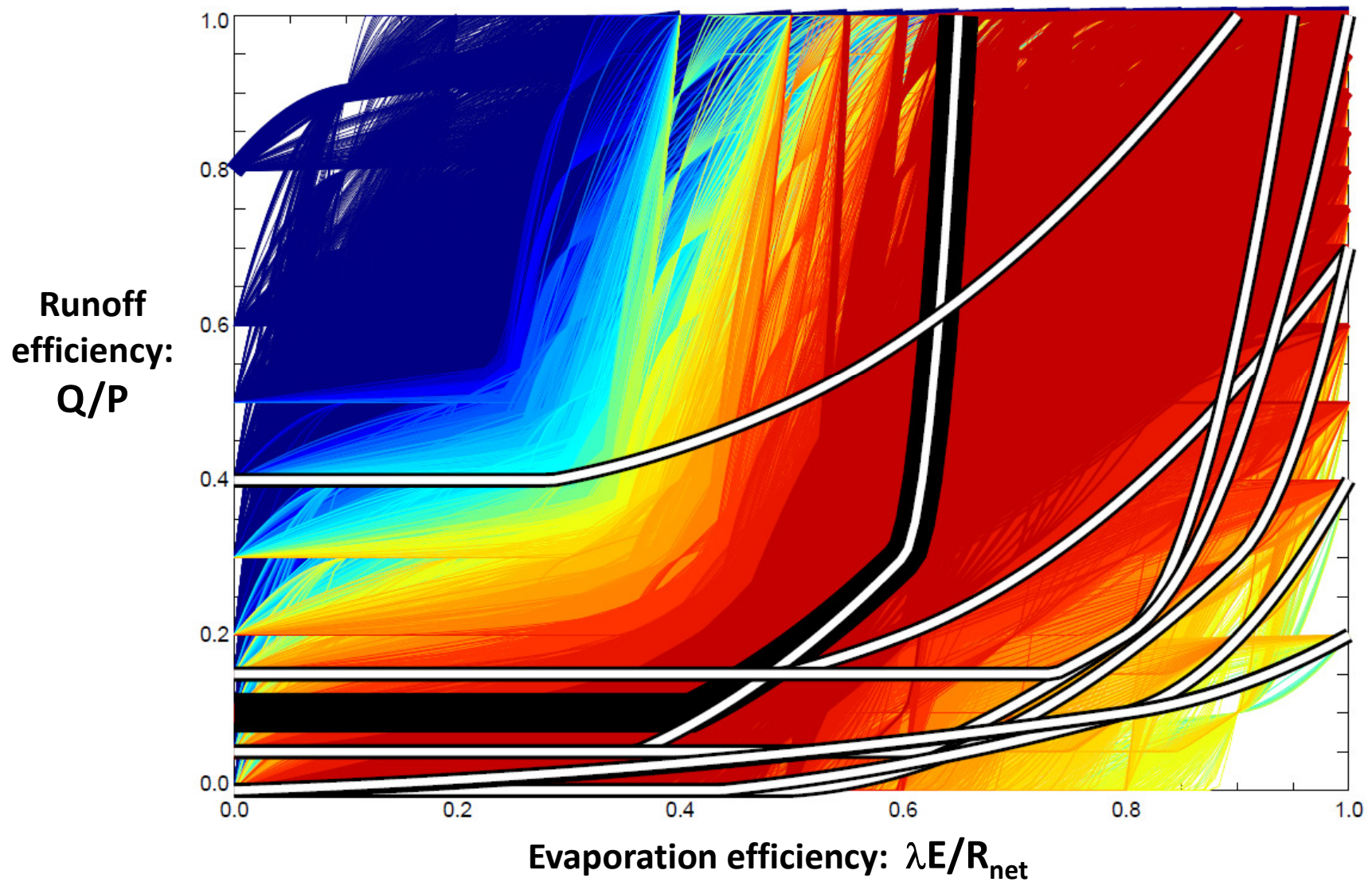


Annual mean Q / Annual mean P



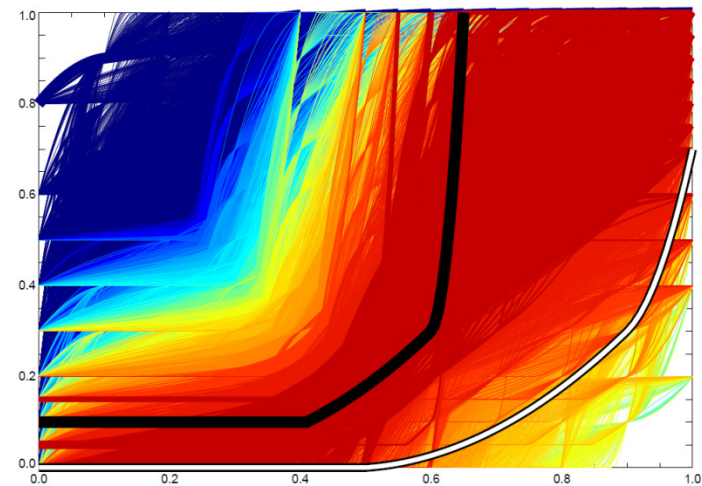
As expected, model Y tends to underestimate runoff ratios.

A number of full land surface models were examined in this way; the results show where “state-of-the-art” models lie in “efficiency space”.



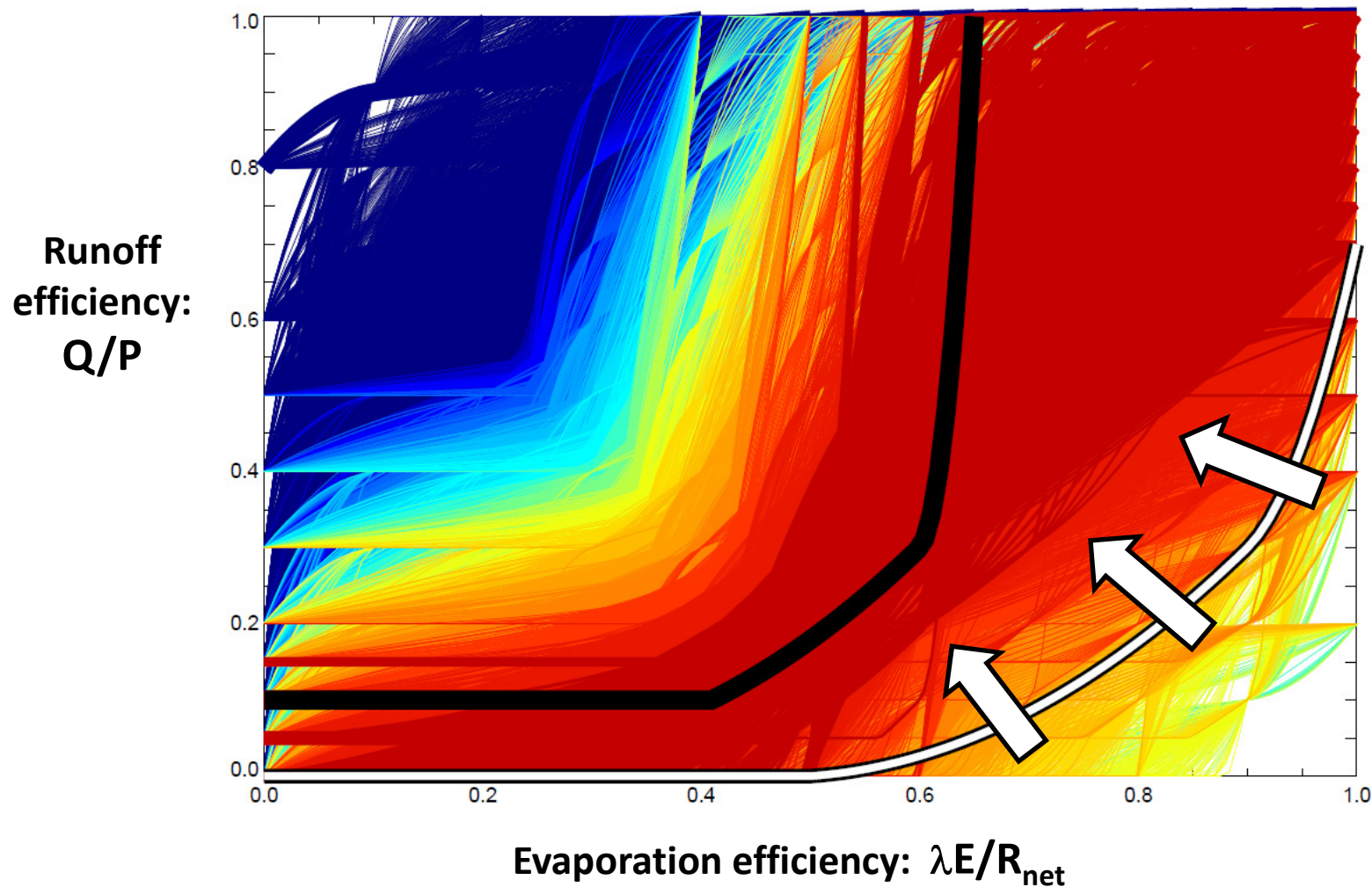
Model Y on the earlier plot was actually the Catchment-CN model, a new version of the NASA/GMAO Catchment model that includes dynamic phenology and photosynthesis modules from NCAR's CLM4.

Can we use “nature’s optimal efficiency relationship” to improve Catchment-CN’s performance?



Yes, via at least 2 approaches...

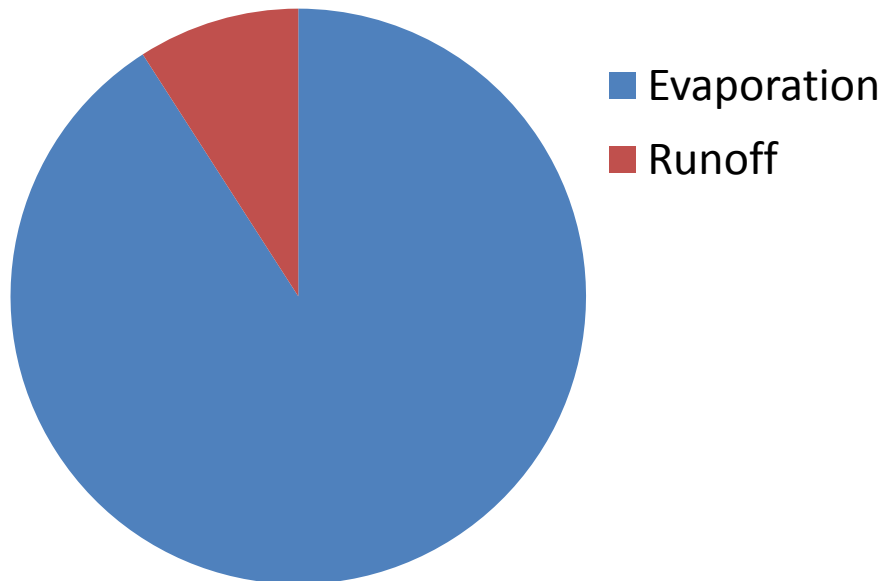
Approach #1 ([DIFFICULT](#)): Keep plugging away at the evaporation and runoff formulations, making them more and more realistic. Eventually the model's curve should approach “nature's curve”.



Approach #2 ([Less satisfying, but much easier](#)): Recognize which parameterizations in the model are weakest, and then tune these parameterizations using “nature’s curve”. Example:

Step 1: Assume (for this example) that evaporation scheme is superior to runoff scheme

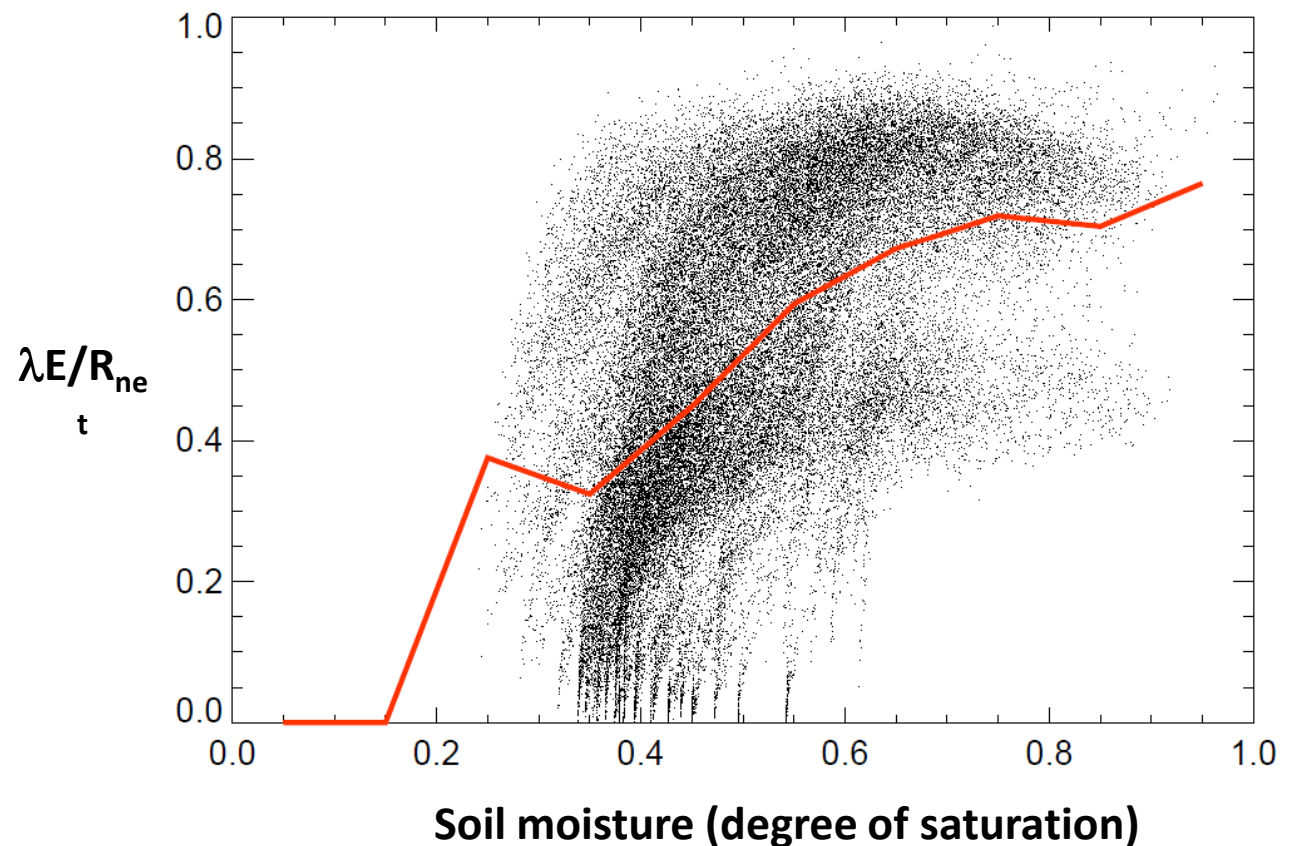
Relative Effort Expended in Developing Different Aspects of a Typical Land Model (Arbitrary, "Gut-based" Estimates)



Approach #2 (Less satisfying, but much easier): Recognize which parameterizations in the model are weakest, and then tune these parameterizations using “nature’s curve”. Example:

Step 1: Assume (for this example) that evaporation scheme is superior to runoff scheme

Step 2: Compute the model’s evaporation efficiency function

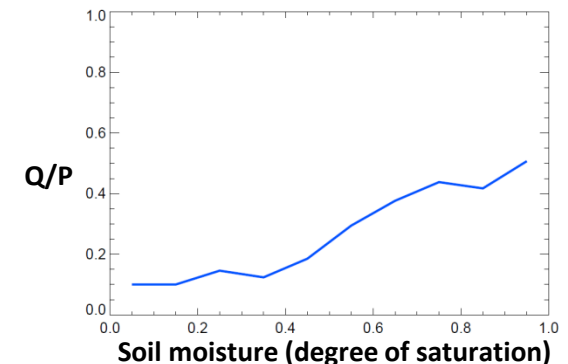
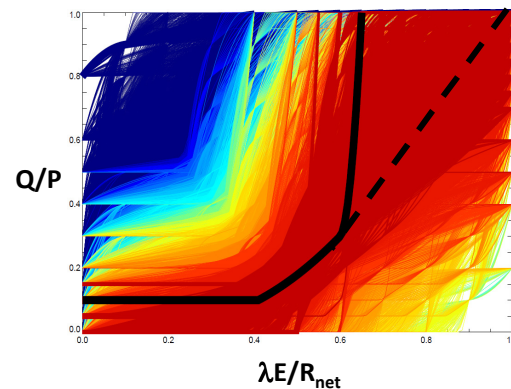
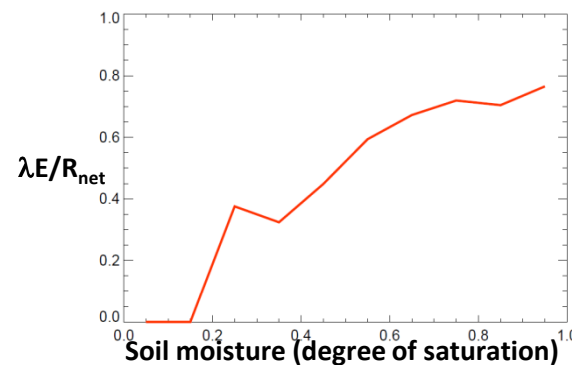


Approach #2 (Less satisfying, but much easier): Recognize which parameterizations in the model are weakest, and then tune these parameterizations using “nature’s curve”. Example:

Step 1: Assume (for this example) that evaporation scheme is superior to runoff scheme

Step 2: Compute the model’s evaporation efficiency function

Step 3: Using something close to “nature’s curve”, compute the corresponding optimal runoff efficiency function



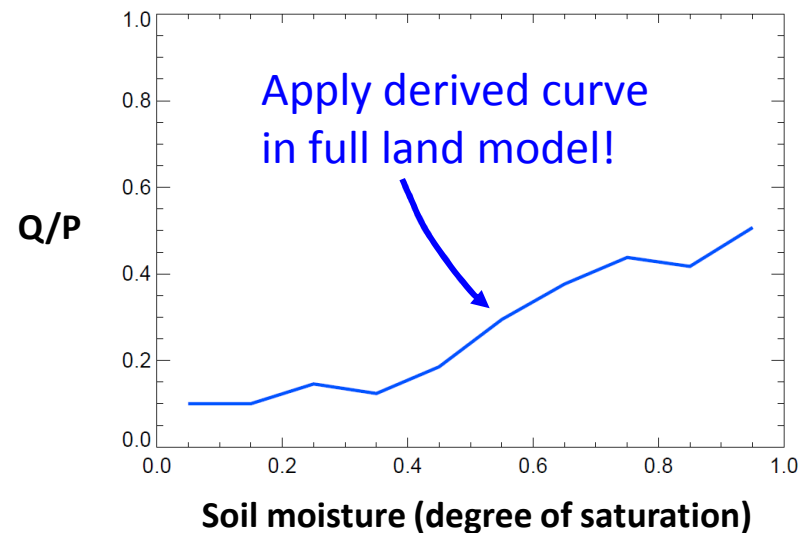
Approach #2 (Less satisfying, but much easier): Recognize which parameterizations in the model are weakest, and then tune these parameterizations using “nature’s curve”. Example:

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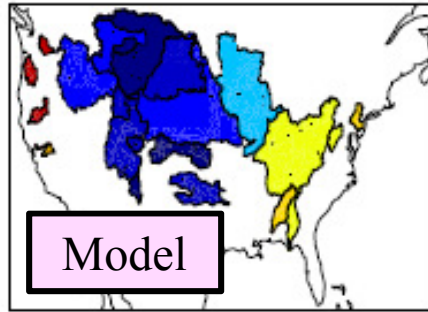
Step 2: Compute the model’s evaporation efficiency function

Step 3: Using something close to “nature’s curve”, compute the corresponding optimal runoff efficiency function

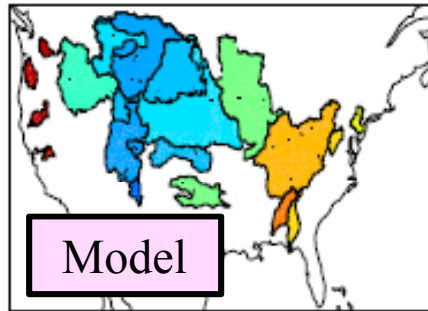
Step 4: Modify the runoff formulations so that (effectively) this function is used directly



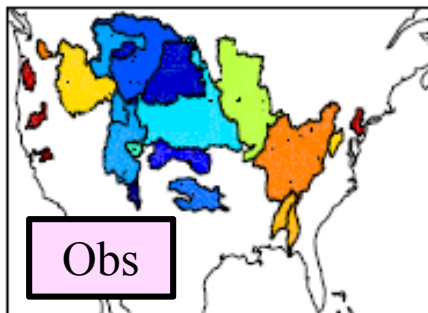
Runoff ratios: Annual mean Q / Annual mean P



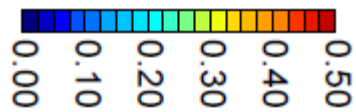
Original Catchment-CN model



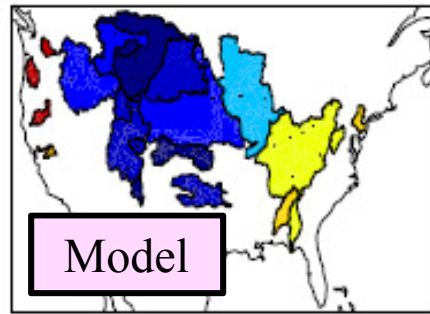
Tuned Catchment-CN model



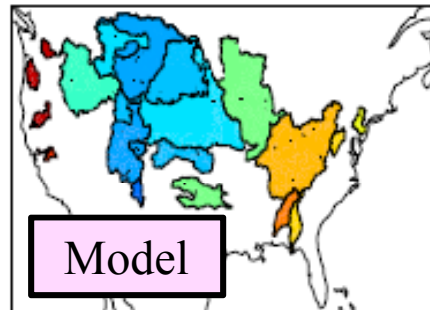
Observations



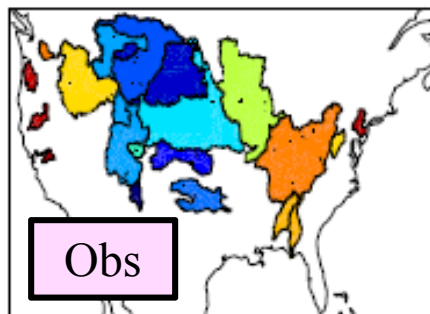
Runoff ratios: Annual mean Q / Annual mean P



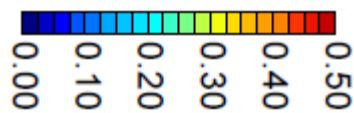
Original Catchment-CN model



Tuned Catchment-CN model



Observations



The tuned, WBM-based runoff function, operating inside a full land surface model, does produce improved results!

Outline of talk

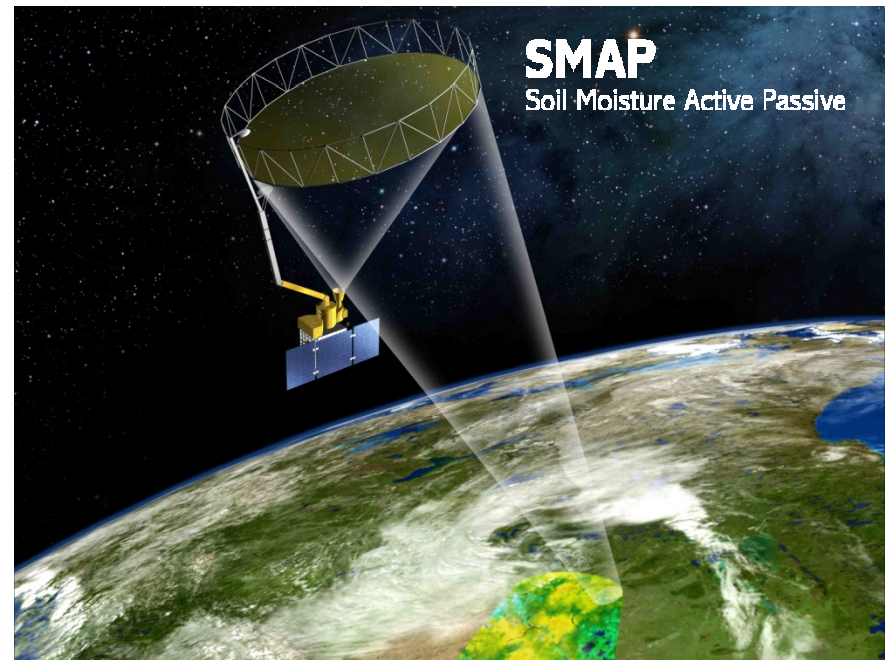
1. Efficiency relationships
2. The “Budyko-istic” perspective
3. Relevance to land surface model development
- 4. Soil moisture: Nature’s linchpin**

As shown above, using “efficiency space” allows us to examine land model formulations while avoiding issues associated with model-specific soil moisture.

This does not mean, however, that soil moisture information for this kind of study is irrelevant – quite the opposite!

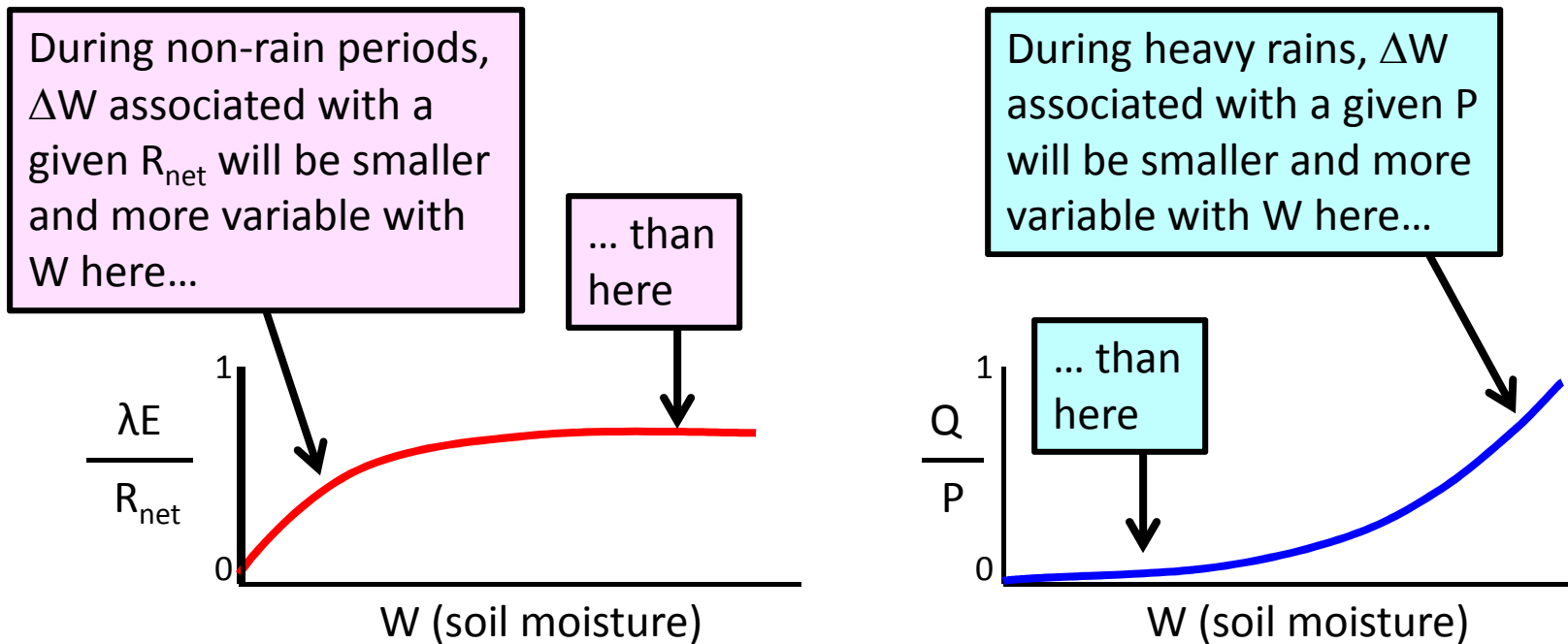
Consider:

1. While evaporation efficiency and runoff efficiency vary with each other, mechanistically both vary with soil moisture.
2. Instantaneous evaporation efficiency and runoff efficiency at the large scale are essentially inaccessible. However, instantaneous large-scale soil moisture measurements are possible, e.g., through the SMOS and SMAP satellite missions.

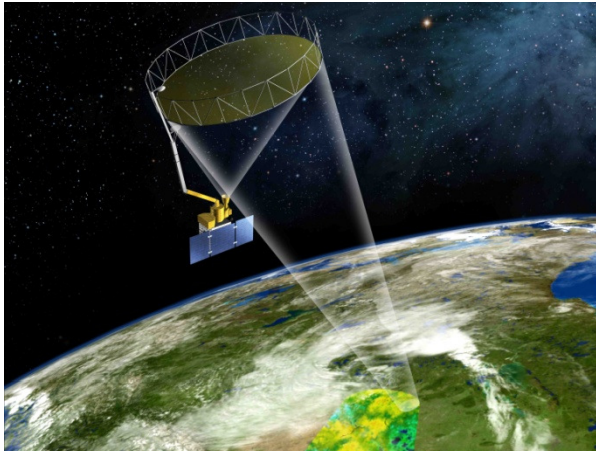


Consider:

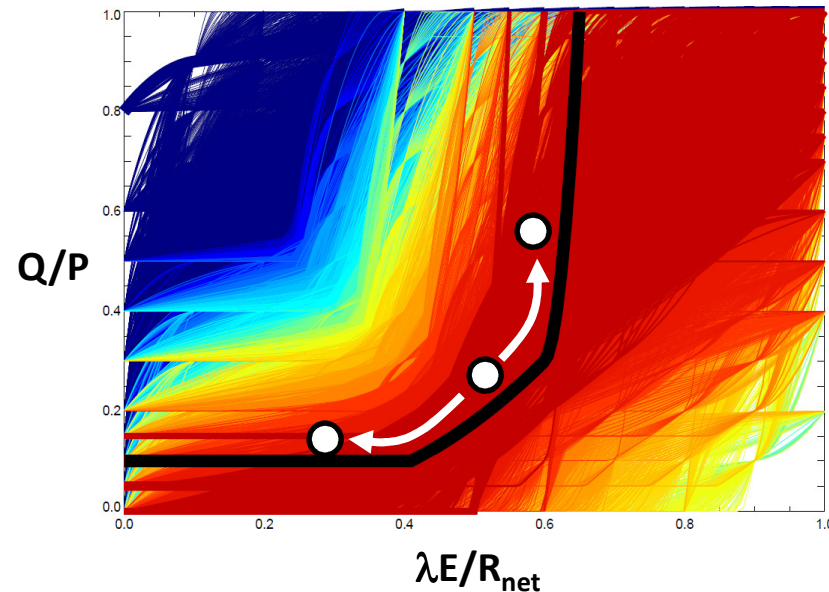
3. The forms of the evaporation and runoff efficiency functions should impart distinct signatures on soil moisture variations.



These considerations lead to intriguing questions:



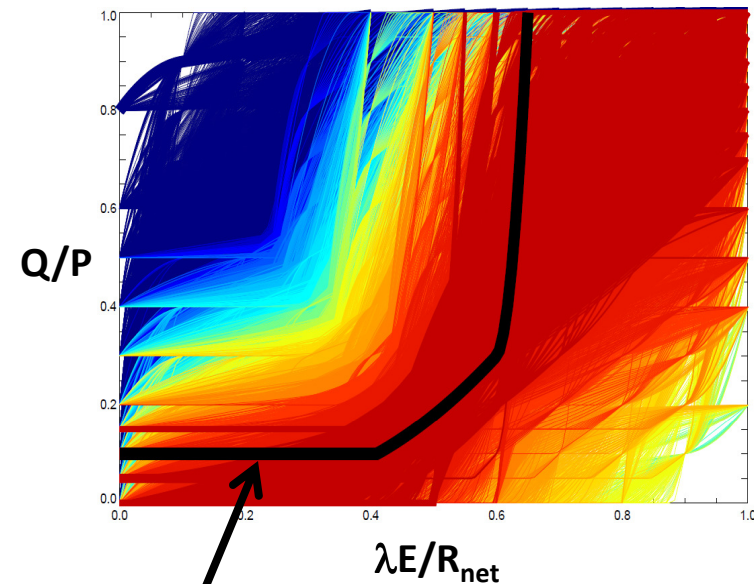
Could the analysis of
SMAP or SMOS
measurements...



... tell us where we are on the optimal
curve at any given time – i.e., **how the
region is behaving hydrologically at
that time?** Can they even help us
**constrain better the location of the
curve?** The possibilities are exciting...

(Brief) Summary

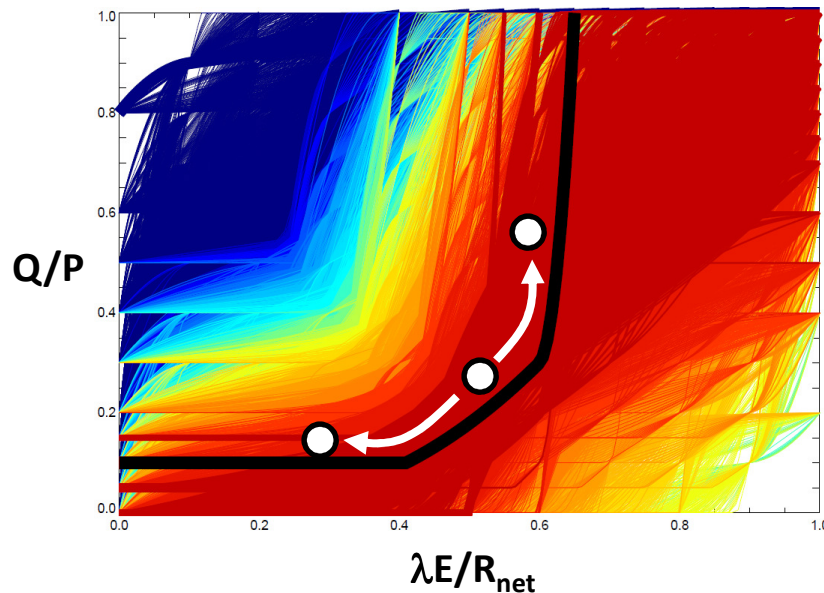
1. The “efficiency-space” plot is presented as an alternative framework for examining surface hydrology – *a framework that emphasizes the joint control of evaporation and runoff processes on hydrological behavior.*



Identifying the position of a region's optimal curve in this space is tantamount to characterizing much of its surface hydrology.

(Brief) Summary

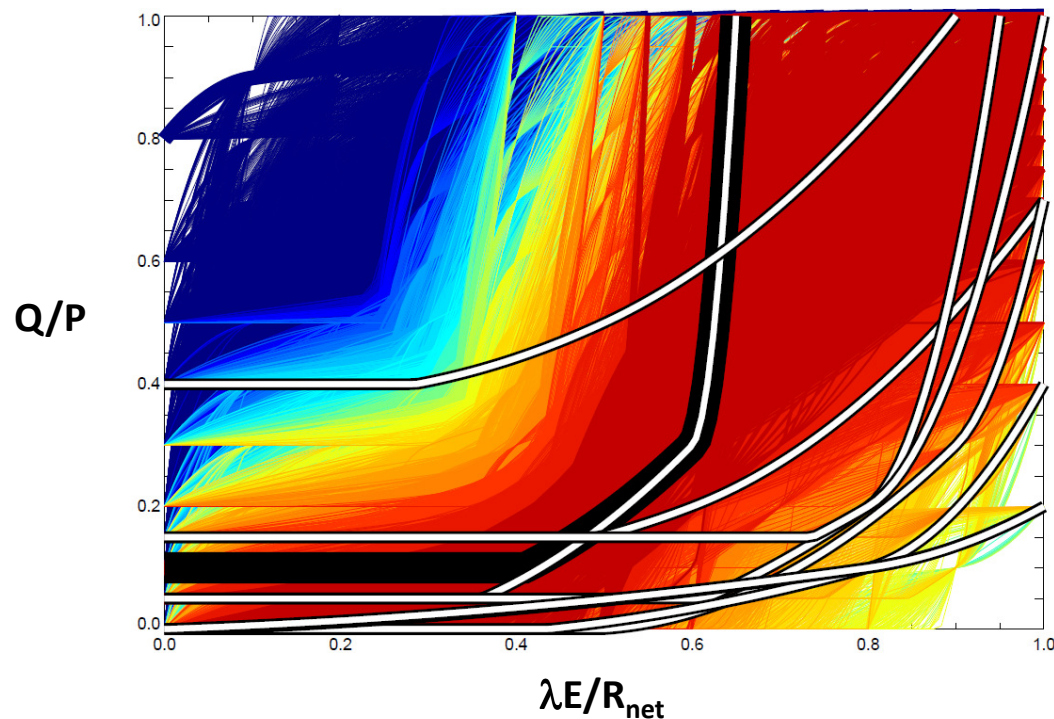
2. The ideas behind the framework are not wholly new – Budyko (for example) used similar ideas in studying climatological runoff and evaporation.



Here, though, the focus is on the relationship between time-varying changes in instantaneous evaporation and runoff efficiencies at a given location – the type of variations that need to be accounted for in land surface models.

(Brief) Summary

3. The framework could serve as a tool for evaluating and improving land surface models. If a model performs poorly against observations, its effective curve is probably in the wrong position – *its balance between evaporation and runoff efficiency is probably off.*



It's a nice way to characterize and evaluate a land surface model's hydrological behavior – and it points to needed directions for improvement!

That's all...

Thanks!